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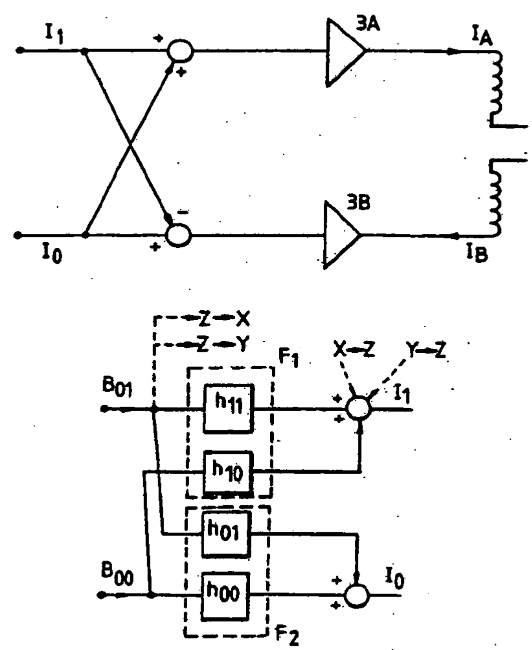
(57) Abstract

A control system for a gradient field generator, suitable for example for an NMR apparatus, includes filters which modify the field demand signal. The modification shapes the gradient field profile typically to compensate for the response characteristics of the NMR apparatus. Current generators (3a, 3b) supply currents to a plurality of individually magnetisable windings. The filters include different filters (F_0, F_1) corresponding to matrix currents (I0, I1) of different orders. The outputs of the different filters are summed to provide a control input for one of the current generators, and subtracted to provide the control input for the other of the current generators. The system thereby provides substantially decoupled control of the different field orders.



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GRADIENT FIELD CONTROL

TECHNICAL FIELD

The present invention relates to a method and apparatus for controlling the gradient field in an NMR apparatus. It is applicable to any type of NMR apparatus including superconducting, resistive electromagnetic or permanent magnetic systems.

BACKGROUND

In typical NMR imaging and spectroscopy apparatus a main magnet is provided for generating a homogeneous steady axial field. In addition, a number of gradient coil sets are also provided. These superimpose gradients on the main field in order to localise a working volume of uniform magnetisation within the apparatus for investigation of the sample at that position.

In use, a pulse is applied to the gradient coils and the subsequent free induction decay (FID) signal from the sample is sensed. While ideally the output of the coil would vary as a step function, in practice imperfections in the dynamic response of the gradient coils means that the shape of the output field pulse tends to be degraded. In particular, it may be found that a large z_0 term, equivalent to a time-varying shift in the main magnetic field B_0, is generated as a result of eddy currents in the apparatus. These fields occur, for example, in the metal components making up the coil housing or NMR apparatus.

It has previously been proposed to use compensation techniques of the type known in control engineering as "feedforward" in order to compensate for these imperfections in the dynamic response of the gradient field coils. This is widely known as pre-emphasis where the flux lags the current and emphasis is needed on the current to give a flat flux response. At their simplest, these techniques might involve the insertion of a multi-exponential signal shaping network in the feed to the

existing gradient coil. Typically between two and five time constants are set based on a mixture of measurement and empirical methods.

US-A-4585995 in the name of Flugan, for example, discloses a system in which an overshoot current is provided to a gradient coil during gradient switching. The shape of the pre-emphasis signal is determined by a time constant network.

With simple pre-emphasis techniques of the type described above, it is not possible fully to compensate for the imperfections in the response of the gradient coil. This results, in part, from the cross-coupling of the different spatial orders of the field in the gradient coils. This means, in a z gradient for example, changes in the z field will also alter the z_0, X, Y fields and even higher field orders.

In an attempt to overcome the limitations of these simple pre-emphasis techniques, it has been proposed to shape the signals applied to multiple coils. In the paper by P. Jehenson et al published at pp 264-248, Journal of Magnetic Resonance 90, (1990) a system is described in which there is provided an additional z_0 coil. Separate pre-emphasis networks independently shape the signals fed to both the gradient coils and to the additional z_0 coil (see for example Fig. 3(A) of the cited paper).

These prior art systems have a number of limitations. The cross-coupling compensation cannot in general be exact since the approaches adopted rely upon the assumption that certain cross-coupling terms are small. Secondly, they require the use of an extra winding which adds an extra degree of coupling control, e.g., a z_0 winding to compensate for z_0 cross-coupling effects. This is not always possible in practice. A further limitation is that the prior art techniques can only approximately model the eddy currents using a finite number of coupled coils and the use of a larger number of coils can make the Laplace

transform method unwieldy, requiring that a large number of time constants should be used for the filter network.

SUMMARY OF THE INVENTION

According to a first aspect of the present invention, there is provided a control system for a gradient field generator for use in an NMR apparatus, the control system including filter means arranged to modify a field demand signal so as to shape the gradient field profile, and

current generators arranged to supply current to a plurality of individually magnetisable windings,

in which the filter means include different filters corresponding to dynamic matric currents (I_0, I_1) of different orders, and in which the outputs of the different filters are summed to provide the control input for one of the current generators, and subtracted to provide the control input for another of the current generators, the system thereby providing substantially decoupled control of a plurality of individually magnetisable windings.

The method of the present invention, by contrast with the prior art system, provides decoupled control of the different fields orders using the combination of a number of individually magnetisable windings without requiring the use of any additional coils. This is achieved by decoupling the real current feeds for the windings into "dynamic matrix currents" corresponding to respectively even and odd order terms of the fields to be generated by the windings. Separate filters can then be provided for each of the matrix currents. The outputs of the different filters are then summed to give the current input for one winding and the difference taken to provide the current input for the other winding. In this manner the control system provides decoupled control of the different field orders. The method of the present invention can be applied to any type of magnet producing a DC field which has a gradient field superimposed. The actual form of the windings depends on the particular application and the

preferred field strength, order of the field gradient, pulsed field profile, heating effects, and complexity of the power supply and control system.

Preferably the plurality of windings comprise different parts of a single gradient coil.

The different windings may be provided, for example, by the left and right parts of the axial (z) gradient coil or, for example, by the inner and outer parts of an x gradient coil or a y gradient coil. The different halves of such coils are readily accessed using centre taps. In the example described in further detail below, for the axial z gradient the sum of current inputs to the two parts of the winding (labelled A and B) produce odd order terms and these are used to generate the required z gradient. The difference windings of A and B produce even order terms and it is these which are used to compensate for the z_0 field shift. In practice of course the nature of the physical connection to the different windings remains unchanged and "sum" or "difference" connections are effected by an appropriate change in the signs of the feeds to the respective windings.

The filter means may comprise a number of discreet analogue filters with appropriately chosen time constants, or may be implemented by appropriate digital signal processing controlled by software.

As a preferred option, the control system may further comprise a feedback loop arranged to sense a variation in a particular field order generated by the plurality of windings and to modify the corresponding matrix current accordingly.

A further major advantage of the present invention is that by providing decoupling it makes it possible to construct feedback loops for individual field orders. The flux associated with a particular order can be measured from the induced EMF in the winding, or alternatively an equivalent search coil may be provided for this purpose. Other techniques having suitable dynamic response and

sensitivity may be used. In particular, it may be advantageous to measure the individual field orders directly on the basis of NMR measurements.

Preferably the feedback loop includes an AC coupled integrator.

Since perfect control of the feedback loop is not possible the DC level will eventually become arbitrary. For this reason it is preferred that the integrator should be AC coupled. The filtering of the AC coupled integrator is then allowed for in the overall control strategy.

A variety of different methods may be used to set the filter values for the control system but it is much preferred that this is done by measuring the frequency response of the system and calculating complementary response curves. The response curves may then be used directly to modify the feed signal in the case of a digitally implemented signal, or for a system using discrete analogue filters the time constants may be fitted to the curve using, e.g., a least-squares method. In either case, this approach avoids the inaccuracies resulting from attempting to identify eddy-current time constants. In the case of the directly digitally modified signal this method avoids altogether the need to identify filter time constants. This novel approach to determining values for the filters is not limited in application to control systems in accordance with the first aspect of the present invention but can also advantageously be used to determine the filter values for different types of feedforward control systems for gradient field generator windings.

According to a second aspect of the present invention, there is provided a method of determining the filter values for a feed forward control system for a gradient field generator for use in an NMR system, comprising injecting currents into windings of the gradient field generator at a number of different frequencies, measuring the field strength at the different frequencies so as to determine

response curves, calculating the inverses of the response matrix at the different frequencies, determining from the inverse values corresponding inverse response curves, and setting the filter means in the feed forward control system to give response characteristics substantially matched to the inverse response curves.

The steps of injecting current at different frequencies and measuring the response may carried out directly on the control circuits or alternatively may be carried out using a computer model of the system, in which case the steps are implemented by equivalent mathematical operations.

According to a third aspect of the present invention, there is provided a method of controlling a gradient field generator for use in a NMR apparatus, the method including determining response characteristics of the apparatus and modifying a field demand signal so as to compensate for the response characteristic, in which different elements of the matrix having dimensions corresponding to different orders of the field demand and different orders of the field response respectively are determined and the field demand signal is subsequently modified in accordance with the inverse of the matrix.

Although it is preferred that this third aspect of the present invention is used in combination with the first and second aspects above, nonetheless the use of matrix inversion techniques still give advantages in otherwise conventional NMR gradient field generators, such as those disclosed in the prior art documents cited above. As discussed in further detail below, the demand signal may be modified in accordance with the inverse matrix either by direct matrix inversion using filters corresponding to the elements of the inverted matrix, or by combining the use of filters with feed back of all cross-coupling terms. The filters are then in feed back loops and these loops cannot be guaranteed to be stable. In practice however in most instances especially when cross-coupling is modest,

stability is possible. The filter network with feedback then responds exactly as the inverse matrix system.

BRIEF DESCRIPTION OF THE DRAWINGS

One example of system in accordance with the present invention will now be described in detail and the theoretical background to the invention further discussed with reference to the accompanying drawings, in which:

Figure 1a is a diagram showing schematically the transforming of matrix currents I_1 I_0 to the winding currents;

Figure 1b is a diagram showing the relationship between the matrix currents and the different field orders;

Figure 1c shows the ideal inverse matrix compensation network;

Figure 1d shows an alternative implementation of the matrix inversion using feedback;

Figure 2 is a circuit diagram for an analogue filter for use in the systems of Figure 1;

Figures 3a - 3h are response curves for the system;

Figures 4a - 4h are inverse response curves;

Figure 5 is a diagram showing a shielded gradient winding;

Figure 6 is a schematic showing the transfer function of a typical multiexponential filter;

Figures 7a and 7b are diagrams showing typical axial z gradient and axial x gradient coils respectively;

Figure 8 is a circuit diagram and schematic of coil windings;

Figures 9a and 9b are a circuit diagram of a first printed circuit board used in the preferred embodiment; and

Figures 10a and 10b are a circuit diagram of a second circuit board used in the preferred embodiment.

DESCRIPTION OF PREFERRED EXAMPLE

Figure 1a shows schematically one example of a control system embodying the present invention. The system has an

input 1 which receives a magnetic field demand signal. In the presently described example, the demand signal contains only a first order term B_1, since the required field response is a step function in the field gradient, without any change in the constant zeroth order field B_0. Accordingly in practice the second demand input 1′ would not be used unless required for a more general gradient control system.

The demand signal is fed to a filter system 2. This comprises a first filter pair F_1 which provides an output which determines the first order matrix current I_1 and a second filter pair F_0 which provides the output determining the zeroth order matrix current I_0. The sum of the outputs of F_1 and F_0 provide the control input to a first current amplifier 3A. The difference between the outputs of F_0 and F_1 similarly provide the control input to a second current amplifier 3B. These amplifiers feed respective windings z_A and z_B which in the present example are two halves of the axial z gradient winding. In use, typically a step function is applied as the input signal at the input 1. This results in a generally corresponding rise in the outputs from the current amplifiers feeding the respective windings.

The field generated by the windings however does not perfectly track the rise in the applied current, but includes in addition time-varying fields resulting from eddy currents in the coils, and in other portions of the apparatus.

In the formalism adopted for the theoretical discussion below, the total field B generated in the system is related to the current I in the windings by a function G. In the feed forward technique adopted in the present invention the filters used to shape the field demand signal are arranged to have a response equivalent to G^{-1}. Then, in the ideal case, the field generated by the windings perfectly tracks the demand signal.

Consider a set of m_I windings whose currents can be represented as a vector

$[I]=[I_1,I_2\ ..I_{ni}...I_{mi}]^T$

The magnetic field can be analysed in, say m_B components (eg Legendre components Z,X,Y,XX, or fields at key points)

$[B]=[B_1..\ B_{nB}...B_{mB}]^T$

For such a system the steady state the two can be related by the matrix $[G_{ss}]$:

$[B]=[G_{ss}][I]$

Where the input is dynamic, however, and the co-efficients are a function of frequency and it is necessary to take a frequency transform such as the Fourier Transforms:

$[B(j\omega]=[G(j\omega)[Ij\omega)]$

The "$j\omega$" must be replaced for other transform (eg "s" for Laplace transform).

Conversely, the current response may be determined from the demanded field as:

$[I(j\omega]=[G(j\omega)]^{-1}[B(j\omega)]=[H(j\omega)[B(j\omega)]$

If one has the same number of degrees of freedom (m_I) and variables to control (m_B) then $m_I=m_B$ and a matrix of filters $[G(j\omega)]^{-1}$ will enable one to control the individual field components exactly. Where $m_I>m_B$ there is more than one exact solution while when $m_I<m_B$ approximate solutions may be found using the pseudo-inverse matrix (least squares). In practice, even if there are enough degrees of freedom, one is only going to implement the filters "approximately".

In the classical pre-emphasis techniques used in the prior art, the eddy currents are modelled as a multi-exponential function and the required filter characteristics determined accordingly. For example, assuming only one eddy-current time constant, the normalised step response is

$$B(t)/Istep=(1-\kappa e^{-t/\tau}) \qquad (6)$$

This is governed by a Laplace transform, but any frequency transform is applicable

$$\frac{B(s)}{I(s)} = 1 - \frac{\kappa s}{(s+1/\tau)} = \frac{(1+s(1-\kappa)\tau)}{(1+s\tau)}. \tag{7}$$

For a flat response a filter is required equivalent to $I(s)/B(s)$ so

$$G(s) = \frac{B(s)}{I(s)} = \frac{(1+s\tau)}{(1+s(1-\kappa)\tau)} \tag{8}$$

This has a step response

$$G(t) = 1 + \frac{k}{1-k} e^{-t/(1-\kappa)\tau} \tag{9}$$

In practice between 2 and 5 time constants are set based on a mixture of measurement and empirical methods.

As discussed above in relation to the prior art, in general such systems can only imperfectly compensate for the response characteristics of the apparatus.

The approach adopted in the present invention is based on the control of "dynamic matrix currents".

In our simplest example we have an axial gradient winding whose left and right hand winding [optionally actively shielded] can be separately magnetised with currents I_A and I_B. By utilising these two degrees of input freedom we are able to have almost decoupled control of two orders z_0 and z_1 with currents.

$$\begin{pmatrix} I_A \\ I_B \end{pmatrix} = \begin{pmatrix} 1 & -1 \\ 1 & 1 \end{pmatrix} \begin{pmatrix} I_0 \\ I_1 \end{pmatrix} \tag{10}$$

The matrix currents I_0 and I_1 are then defined as:

$$\begin{pmatrix} I_0 \\ I_1 \end{pmatrix} = 0.5 \begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix} \begin{pmatrix} I_A \\ I_B \end{pmatrix} \tag{11}$$

It follows from system symmetries that, in the steady state, I_0 will only effect even orders and I_1 odd orders. The fields are, therefore, related to the currents by equation

$$\begin{pmatrix} B_0 \\ B_1 \end{pmatrix} = \begin{pmatrix} g_{00} & 0 \\ 0 & g_{11} \end{pmatrix} \begin{pmatrix} I_0 \\ I_1 \end{pmatrix} \tag{12}$$

However, dynamic responses necessitate taking the frequency transform, the Fourier transform being used here.

Furthermore, other effects, such as structural conductor asymmetry and winding imperfection mean that the cross terms are relevant and one gets

$$\begin{pmatrix} B_0(j\omega) \\ B_1(j\omega) \end{pmatrix} = \begin{pmatrix} g_{00}(j\omega) & g_{01}(j\omega) \\ g_{10}(j\omega) & g_{11}(j\omega) \end{pmatrix} \begin{pmatrix} I_0(j\omega) \\ I_1(j\omega) \end{pmatrix} \qquad (13)$$

which can be represented in matrix terms as:
$[B(j\omega)]=[G(j\omega)][I(j\omega)]$

This approach relies upon the fact that gradient and shim windings are built of components which can usually be separated into symmetrical physical sections. The sections then are separated into two halves A and B. For example, a Z gradient might be separated into a left and right half. In an X gradient it is separation into two facing sections 180° apart that is relevant for the present purposes.

The fields due to any section may be analysed by Legendre polynomials into coefficients of given orders (m,n). The effective winding principle takes advantage of the separation of odd and even orders in the physically and electrically symmetrical A and B sections.

Note that the sign convention is arbitrary so, for example, Section B may have both signs inverted. It would then be the Difference that produces the "desired" orders.

Section A={odd in m and/or n} + {even in m and or n}
Section B = {odd in m and/or n} - {even in m and or n}
½ Sum = {odd in m and/or n} [desired component]
½ Difference = {even in m and/or n} [not desired]

<u>Examples for Z and X Gradients</u>

(1) Z gradient : ideally produced (m,n)=(0,1) but, at best, will produce other terms (0,odd)

Z_A = (m=0,n=odd) + (m=0,n=even)
Z_B = (m=0,n=odd) - (m=0,n=even)

Sum = $\frac{1}{2}(Z_A + Z_B)$ = {m=0,n=odd}
Difference = $\frac{1}{2}(Z_A - Z_B)$ = {m=0,n=even}

(2) X gradient: ideally produces (m,n)=(1,1) but, at best, will produce other terms (odd,odd)

X_A = {m=odd,n=odd} + {m=even,n=even}

X_B = {m=odd,n=odd} - {m=even,n,even}

Sum $=\frac{1}{2}(X_A+X_B)$ = {m=odd,n=odd}

Difference $=\frac{1}{2}(X_A - X_B)$ = {m=even,n=even}

Tables 1a and 1b show for the different orders of the Legendre polynomial expansion the contributions to the field of the A and B sections, together with the sum and difference of those contributions. Table 1a and the corresponding Figure 7a relate to a typical axial Z gradient, while Table 1b relates to a typical transverse X gradient. Considering, for example Table 1a, it can be seen that the difference windings produce large even order fields while the sum winding produces primarily the first order z field.

In the present example the values for the different filters are determined by exciting the windings with matrix currents of different frequencies and measuring the frequency response. Different frequencies of I0 are injected and the strength of the resulting zeroth and first order fields measured, giving the response curves shown in Figures 3a and 3b respectively. Similarly different frequencies of I1 are injected and the zeroth and first order responses measured, giving plots 3c and 3d. At any given frequency these four plots correspond to a 2 x 2 matrix. These matrices are inverted to give the inverse response curves shown in Figures 4a to 4d. In the present example discreet filters are used, with the values of the filters chosen to approximate the inverse response curves by use of exponential fitting methods in the time domain, so that the filter has the same step response. If S(t) is a square wave of unity amplitude and h(jω) is the filter required, then the frequency response of the filter to the step input is

$$y(j\omega) = h(j\omega)\, S(j\omega) \tag{18}$$

and the time response of the filter is found from the inverse Fourier transform,

$$y(t) = F^{-1}(\, h(j\omega)\, S(j\omega)\,) \tag{19}$$

In a digitally implemented system these curves may then be applied directly to shape the demand signal.

Figure 6 shows a schematic for an analogue filter made up of the sum of a number of first order exponential filters. The FFT may be implemented using a discrete Fourier transform. The sample time for the transform must be less than the time constants of interest and the square wave must be of a long enough wavelength such that the slow time constants will have decayed.

Plots f-j in Figures 3 and 4 show the response curves and inverse curves in the time domain.

The above method is applicable equally to shielded and unshielded windings. Figure 5 shows a shielded gradient winding in which a secondary winding is positioned outside the primary winding. The matrix currents may be combined in the primary and secondary windings in a number of different configurations, as shown in Table 2 which relates to an axial gradient. (In the sign convention chosen the current sense is equal to the axial field sense). For the preferred options 1 and 2 listed in the table both the primary and secondary coils are used to generate the B_0 field. Equivalent IA and IB can be produced by connecting the primary and secondary pairs in an uncrossed or crossed configuration. Option 1 shown in Figure 5 uses an uncrossed connection so that the real current in each of the secondaries is opposite in sign to that in the primary, thereby maintaining the active shielding.

As an alternative to the direct matrix inversion method shown schematically in Figure 1(c), feedback may be used to provide a system have the desired matrix inverse characteristics. This is shown schematically in Figure

1(d). Also, the system may be extended to take account of coupling between fields in different directions. Thus, for example, although the systems are described above for correction of the cross-coupling of different spatial orders of the axial (z) field in practice a change in the z field will also be cross-coupled to changes in the x and y fields. The dashed lines in Figures 1(c) and (d) show how connection for the cross-coupling to and from different directions may be added to the basic system.

Figure 2 shows a typical analogue implementation of a compensation filter incorporating three time constants. In practice each block, such as filter element h_{11} in Figure 1 may be implemented by such a filter. The general form of the analogue filters can be represented by the sum of a DC component k_0 and the sum of exponential filters. In terms of Laplace transforms one gets:

$$f_{ij}=k_0+\sum_{i=1}^{n}\frac{k_i s\tau_i}{1+s\tau_i}$$

where the gains k_i and the time constants t_i can be found from the components in the circuit of Figure 2 as:

$$k_i = (2 - \alpha_{2i})\, R5/R4_i$$

$$\tau_i = (R1i + \alpha_{1i}\, RV1i)\, Ci$$

where α_{ij} refers to the wiper setting of the potentiometers (adjustable resistance $RV1_i$ and $RV2_i$) which varies from zero to unity. Typical component values for the circuit are shown in Table 3.

Figures 9 and 10 show in detail one example of a complete circuit incorporating the compensating filter. The different components of the circuit are described below. Because of the limited space available to mount the circuit, it is spread over two PCBs.

<u>Board 1 (Figure 9)</u>

<u>Power Supply</u>

The power input to the PCB is an unregulated +/- 23 volt supply.

Integrated circuit U15 is a +15 volt regulator and together with C10, C18, D5 and D7 supply +15 volt power to the circuit. Similarly U17 is a -15 volt regulator and together with C11, C19, D6 and D8 provide the -15 volt power to the circuit. There are a large number of decoupling capacitor spread evenly about the two PCBs.

Demand Input

The gradient demand input is a differential signal on connector P1 a10 and c10 pins. A 5 volt level between these two pins will constitute a maximum gradient demand. Integrated circuit U1 receives this signal and this is summed with the shim demand by U3. Test Point 6 (TP6) is a monitor point that is the sum of both the gradient demand and the shim demand.

Shim Demand Input

The shim demand input on connector P1 pins a14 and a15 is received by the differential amplifier U2. This signal is then limited in frequency by the low pass filter R9 and C24 with a 3db point of 1.6 Hz. The shim signal is summed with the gradient demand by U3.

Stop Circuit

A 0 volt level on connector pin P1 a11 will reduce the gain of the amplifier U3 to a very small level thereby removing any large gradient demand. This occurs whenever the gradient amplifier is in the STANDBY condition.

BO Circuit

The BO compensation circuits are similar to the cross term circuits. The demand for the BO circuit is only the uncompensated DEMAND signal. There are five signals summed by U10 to form the BO compensation signal BO_OUT. U8a forms a signal that is linearly proportional to the DEMAND signal with a gain set by RV25 between -1 and +1. The four circuits associated with C9 to C12 are similar to the cross

term circuits described above. Circuit U10 sums each of the five BO compensation signals at TP9 to TP12 and TP15. Each compensation is a maximum of +/- 10% of the DEMAND signal.

The three signals CT1_OUT, CT2_OUT and BO_OUT are presented to the connector P1 pins c16, c17, c3 respectively and passed on the amplifier control circuits to drive the required gradient coils.

Slew Rate Limit

When driving an inductive load the demand signal has to be rise time limited to keep the output voltage of the amplifier within its working range. The circuit combination of U4 and U5 generate a linear ramp on the rising and falling edges of the demand signal. The slew rate limit is adjusted by the RV2 potentiometer over a range of 0.1 millisecond to over 1 millisecond of time to full demand.

Eddy Current Compensation

As described above, eddy current compensation is required to get the optimum performance from a MRI system. Depending on the exact requirements of the system this compensation may be required to pre-emphasize or de-emphasize the current demand. The modification is constructed with four available time constants made from four independent circuits associated with capacitors C1, C2, C3 and C4. Each time constant is adjusted with potentiometers RV3, RV5, RV7 and RV9 respectively. The time constants are buffered by U6a, U6b, U7a and U7b. The gain of each time constant can be varied from -1 to +1 with potentiometers RV4, RV6, RV8 and RV10 respectively. Each of the four compensation signals can be monitored on test points TP9, TP10, TP11 and TP12.

Cross Term Demands

Two outputs to the cross term and BO compensation circuits these are DEMAND taken from the slew rate limited input signal but before any compensation is added. CR_DEM is the same signal as the gradient demand output and contains all of the compensation signals as programmed.

Gradient Demand Output

The demand output presented to connector P1 c1 and monitored on TP17 is the sum of the demand input, shim input and any combination of eddy current compensation and cross term combination required. Links LK5 to LK16 together with the adjustment potentiometers are used to program the desired compensation signal.

Power Monitor

The gradient amplifier may be able to deliver larger power than the gradient coil can withstand. A protection circuit is incorporated to monitor the gradient demand signal and to set the amplifier into standby mode if the demand is higher than a set level. Circuit U9, U10 and the associated components form a precision rectifier, TP6 signal is the absolute value of the demand signal. U11 is a transconductance amplifier that is used as a squarer circuit its output is the square of the demand signal. U12 low pass filters this signal. The signal at TP14 is proportional to the square of the output current. This signal level is monitored by the level detector U13. If the TP14 signal becomes more +ve than the level set at TP15 by RV11 then the TP15 signal and connector P1 pin c20 goes to a low (0 volt) level and sets the amplifier in the STANDBY state.

Board 2 (Figure 10)

Cross Term Circuit

The "piggy back" board contains eight cross term circuits in two sets of four. Each of the eight circuits

is identical except for the value of the compensation capacitors C1 to C8. The links LK27 and LK28 select which of the two demand signals are required for the cross compensation. Either the uncompensated DEMAND signal is selected with LK27 or the compensated output demand CR_DEM with LK28.

Referring to one circuit. The time constant is set by the C1, RV1 combination and is buffered by U1b. RV2 sets the compensation gain between -1 and +1. The circuit associated with U7 sums the four compensation signals at TP1 to TP4. The required compensation being selected by the links LK1 to LK8. TP13 forms the first cross term signal CT1_OUT. Each of the compensation circuits can be set to a maximum of +/- 10% of the demand signal.

Similarly for the second cross term signal CT2_OUT the compensation is set with C5 to C8 and RV9 to RV15 components, U8 sums the signals from TP5 to TP8, links LK9 to LK16 select the desired compensation signals.

As noted above, one preferred aspect of the present invention uses feedback based on NMR measurements. In this case the NMR response from a known sample volume is measured across an array of many sampling points. The response is compared with the expected response to derive an error signal which is used in the feedback loop to modify the matrix currents.

TABLE 1

Numerical Example of Effective Windings of A Z and X Gradient

1a LEGENDRE POLYNOMIAL EXPANSION FOR BZ FROM A TYPICAL AXIAL Z GRADIENT

Note: The sum of windings A and B produce the odd order terms required to generate the Z gradient. The difference windings of A and B produce even order terms which can be used to compensate for field shifts.

NAME	LEGENDRE N	M	FIELD STRENGTHS FROM A AND	B	SUM A+B	DIFFE A-B
Z0	0	0	5.2	-5.2	0	10.4
Z1	1	0	79.3	79.3	158.6	0
Z2	2	0	1.8	-1.8	0	3.6
Z3	3	0	5.7	5.7	11.4	0
Z4	4	0	-0.7	0.7	0	-1.4

1b LEGENDRE POLYNOMIAL EXPANSION FOR BZ FROM A TYPICAL TRANSVERSE X GRADIENT

Note: The sum of windings A and B produce the odd order terms required to generate the X gradient. The difference windings of A and B produce even order terms which can be used to compensate for field shifts.

NAME	LEGENDRE N	M	FIELD STRENGTHS FROM REAL A	REAL B	SUM A+B	DIFFE A-B
Z0	0	0	3.6	-3.6	0	7.2
Z1	1	0	0	0	0	0
X	1	1	64.2	64.2	128.4	0
Z2	2	0	-0.2	0.2	0	0.4
ZX	2	1	0	0	0	0
S2	2	2	0.1	-0.1	0	0.2
Z3	3	0	0	0	0	0
Z2X	3	1	-0.1	-0.1	-0.2	0
ZS2	3	2	0	0	0	0
X3	3	3	0	0	0	0

TABLE 2

Virtual Currents in a Split Gradient Winding

	I_{A1}	I_{B1}	I_{A2}	I_{B2}	comment
Virtual I_1					
	$-I_1$	$+I_1$	I_1	$-I_1$	
Virtual I_0					
1 *shielded* option	I_0	I_0	$-I_0$	$-I_0$	(I_{A1}-I_{B1} & I_{A2}-I_{B2})
2 *unshielded* option	I_0	I_0	I_0	I_0	(I_{A1}-I_{B2} & I_{B1}-I_{A2})
3 *primary* option	I_0	I_0			
4 *secondary* option			I_0	I_0	

TABLE 3

Typical CIrcuit Component Values

R2i=10K;R5=10K;

No.	R1i	RV1i	Ci	τ_i (approx)	R4i	k_i
0	n/a	n/a	n/a	n/a	10K	-1 to 1
1	99K	1M0	4µ7	0.5 to 5 s	100K	-.1 to .1
2	99K	1M0	1µ0	0.1 to 1 s	100K	-.1 to .1
3	99K	1M0	0µ22	0.02 to .24 s	100K	-.1 to .1

CLAIMS

1. A control system for a gradient field generator for use in an NMR apparatus, the control system including filter means (2) arranged to modify a pulsed magnetic field spatial profile as a function of time, and

current generators (3A,3B) arranged to supply current to a plurality of individually magnetisable windings,

characterised in that the filter means include different filters (F_0,F_1) corresponding to dynamic matrix currents (I_0,I_1) of different orders, the outputs of the different filters being summed to provide the control input for one of the current generators (3A), and subtracted to provide the control input for another of the current generators (3B), the system thereby providing substantially decoupled control of a plurality of individually magnetisable windings.

2. A system according to claim 1, in which the plurality of windings comprise different (Z_A,Z_B) parts of a single gradient coil.

3. A system according to claim 1 or 2, further comprising a feedback loop including means for sensing a variation in a particular field order generated by the plurality of windings, and means for modifying the corresponding matrix current in response to the sensed variation.

4. A system according to claim 3, in which the feedback loop includes an AC-coupled integrator.

5. A system according to claim 3, in which the means for sensing a variation in a particular field order are arranged to do so on the basis of an NMR measurement.

6. A method of controlling a gradient field in an NMR apparatus including a plurality of individually magnetisable windings, and current generators arranged to supply current to the windings, the method including the steps of modifying a field demand signal so as to shape the gradient field profile, and controlling the current generators in accordance with the modified field demand

signal characterised by the steps of applying the field demand signal to different filters corresponding to matrix currents of different orders, summing the outputs of the different filters to provide the control input for one of the current generators, and subtracting the outputs of the different filters to provide the control input for another of the current generators, the method thereby providing substantially decoupled control of a plurality of individually magnetisable windings.

7. A method according to claim 6, further comprising sensing a variation in a particular field order generated by the plurality of windings, and modifying the corresponding matrix current accordingly.

8. A method according to claim 7, in which the variation is sensed by making an NMR measurement.

9. A method according to claim 6, 7 or 8, further comprising the steps of measuring the frequency response of the NMR system, and calculating complementary response curves, the filters for the field demand signal being determined in accordance with the complementary response curves.

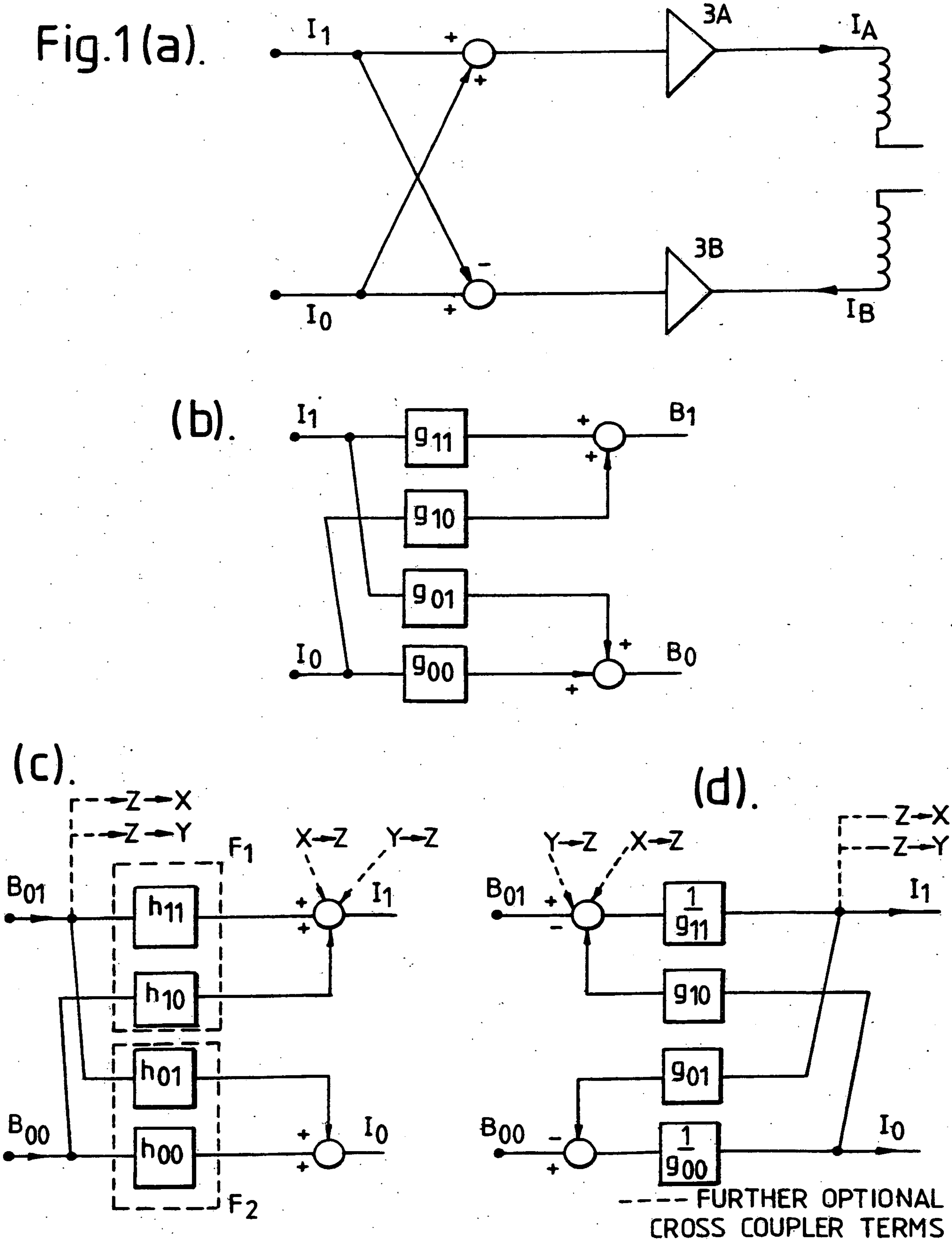
10. A method according to claim 9, in which the step of measuring the frequency response comprises injecting currents into the windings of the gradient field generator at a number of different frequencies, measuring the field strength at the different frequencies and thereby determining a matrix of response curves, and in which the step of calculating complementary response curves comprises determining the inverses of the response curve matrix at the different frequencies, determining from the inverse values corresponding inverse response curves, and setting the filter means to give response characteristics substantially matched to the inverse response curves.

11. A method according to claim 9, in which the step of injecting current at different frequencies and measuring the response are carried out on a computer model of the NMR system.

12. A method of determining the filter values for a feed forward control system for a gradient field generator for use in an NMR system, characterised by injecting currents into windings of the gradient field generator at a number of different frequencies, measuring the field strength at the different frequencies so as to determine response curves, calculating the inverses of the response matrix at the different frequencies, determining from the inverse values corresponding inverse response curves, and setting the filter means in the feed forward control system to give response characteristics substantially matched to the inverse response curves.

13. A method of controlling a gradient field generator for use in an NMR apparatus, the method including determining response characteristics of the apparatus and modifying a field demand signal so as to compensate for the response characteristic, characterised in that different elements of the matrix having dimensions corresponding to different orders of the field demand and different orders of the field response respectively are determined and the field demand signal is subsequently modified in accordance with the inverse of the matrix.

Fig.1(a).


I1
I0
+
+
-
+
3A
3B
IA
IB
(b).
I1
I0
g11
g10
g01
g00
B1
B0
(c).
Z→X
Z→Y
X→Z
Y→Z
F1
F2
B01
B00
h11
h10
h01
h00
I1
I0
(d).
Y→Z
X→Z
Z→X
Z→Y
B01
B00
1/g11
g10
g01
1/g00
I1
I0
FURTHER OPTIONAL CROSS COUPLER TERMS

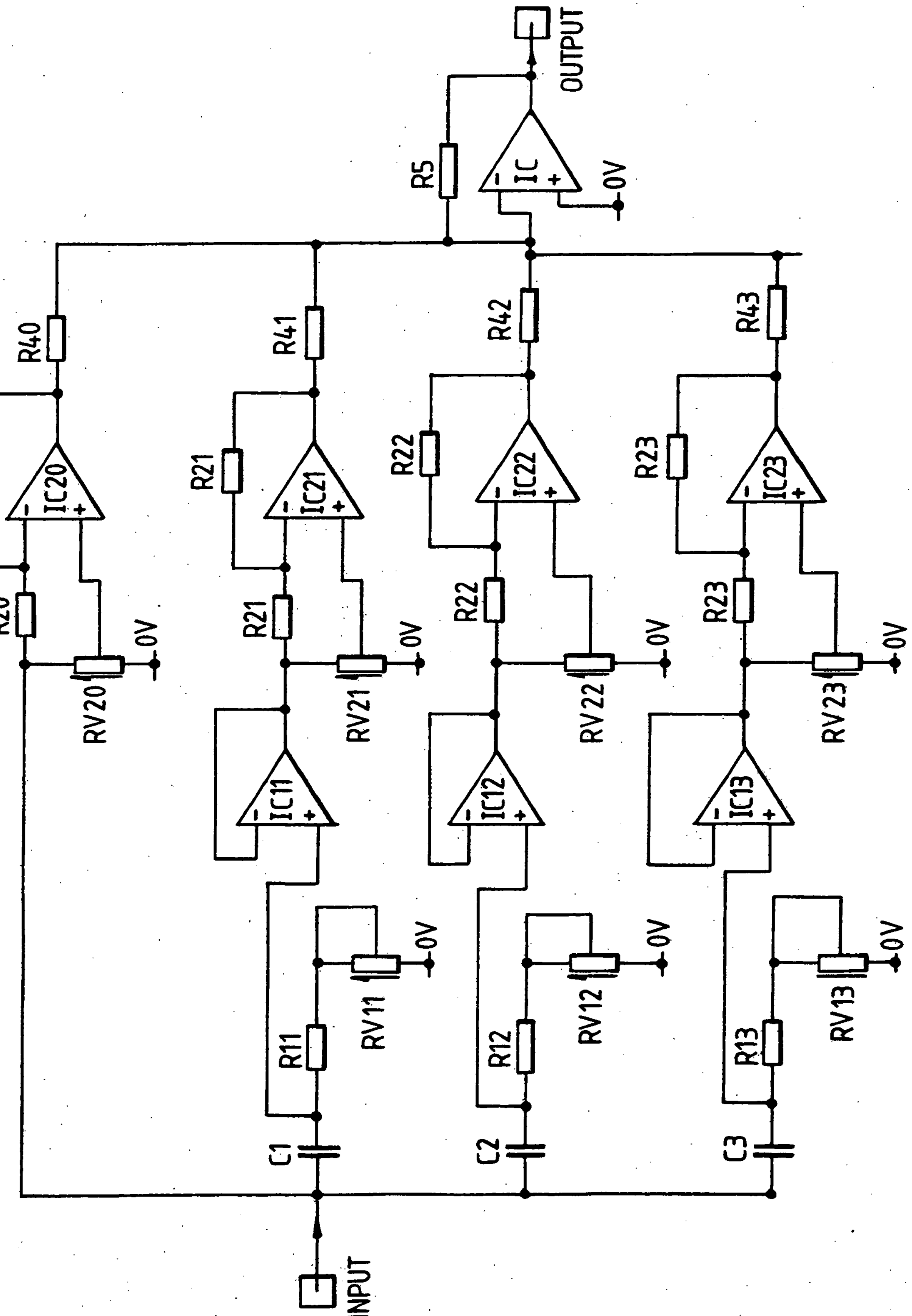

OUTPUT
R5
IC
0V
R40
R41
R42
R43
R20
R21
R22
R23
IC20
IC21
IC22
IC23
RV20
RV21
RV22
RV23
IC11
IC12
IC13
R11
R12
R13
RV11
RV12
RV13
C1
C2
C3
INPUT

Fig.2.

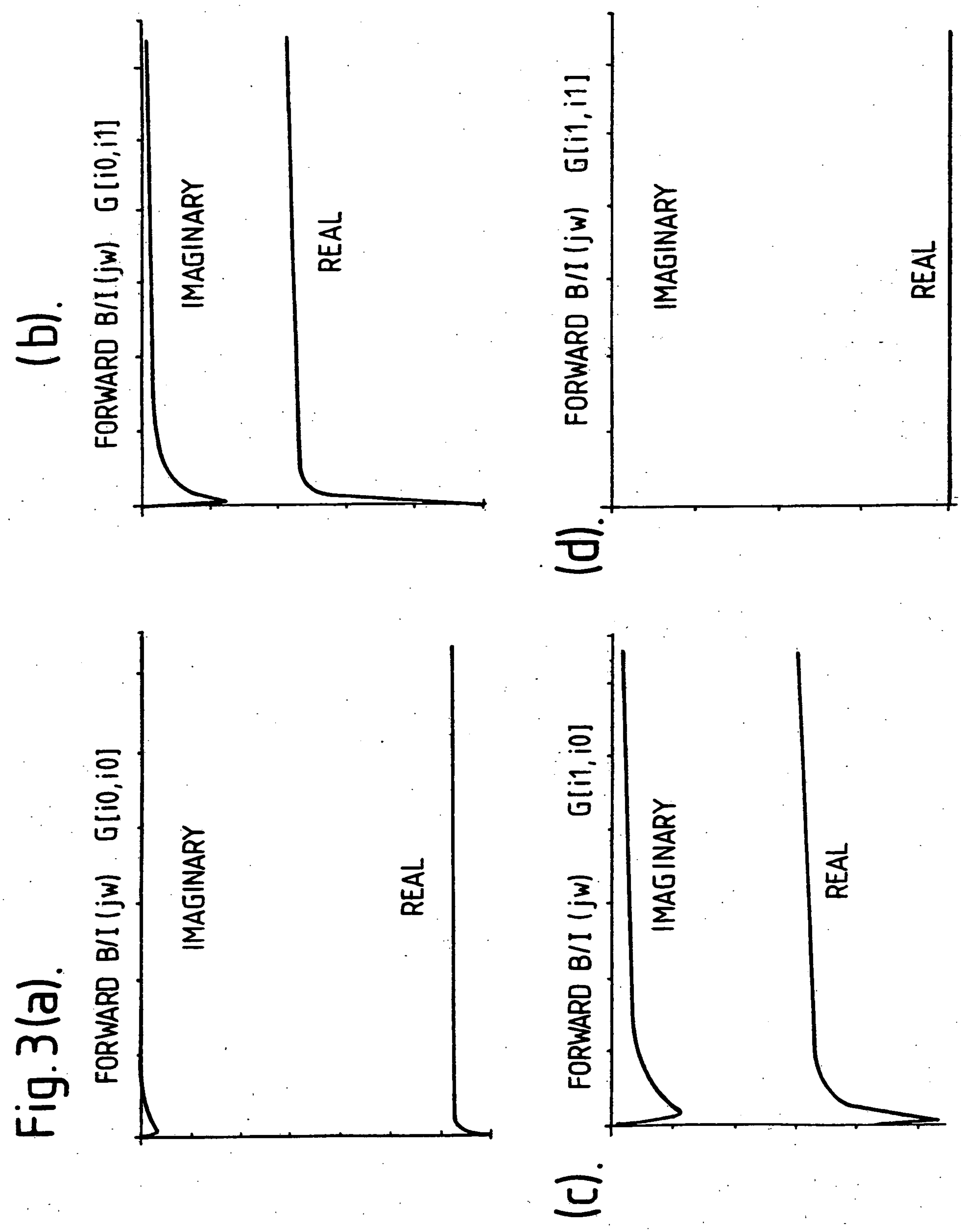

FORWARD B/I (jw) G[i0,i0]
IMAGINARY
REAL
FORWARD B/I (jw) G[i0,i1]
IMAGINARY
REAL
FORWARD B/I (jw) G[i1,i0]
IMAGINARY
REAL
FORWARD B/I (jw) G[i1,i1]
IMAGINARY
REAL

Fig.3(a).

(b).

(c).

(d).

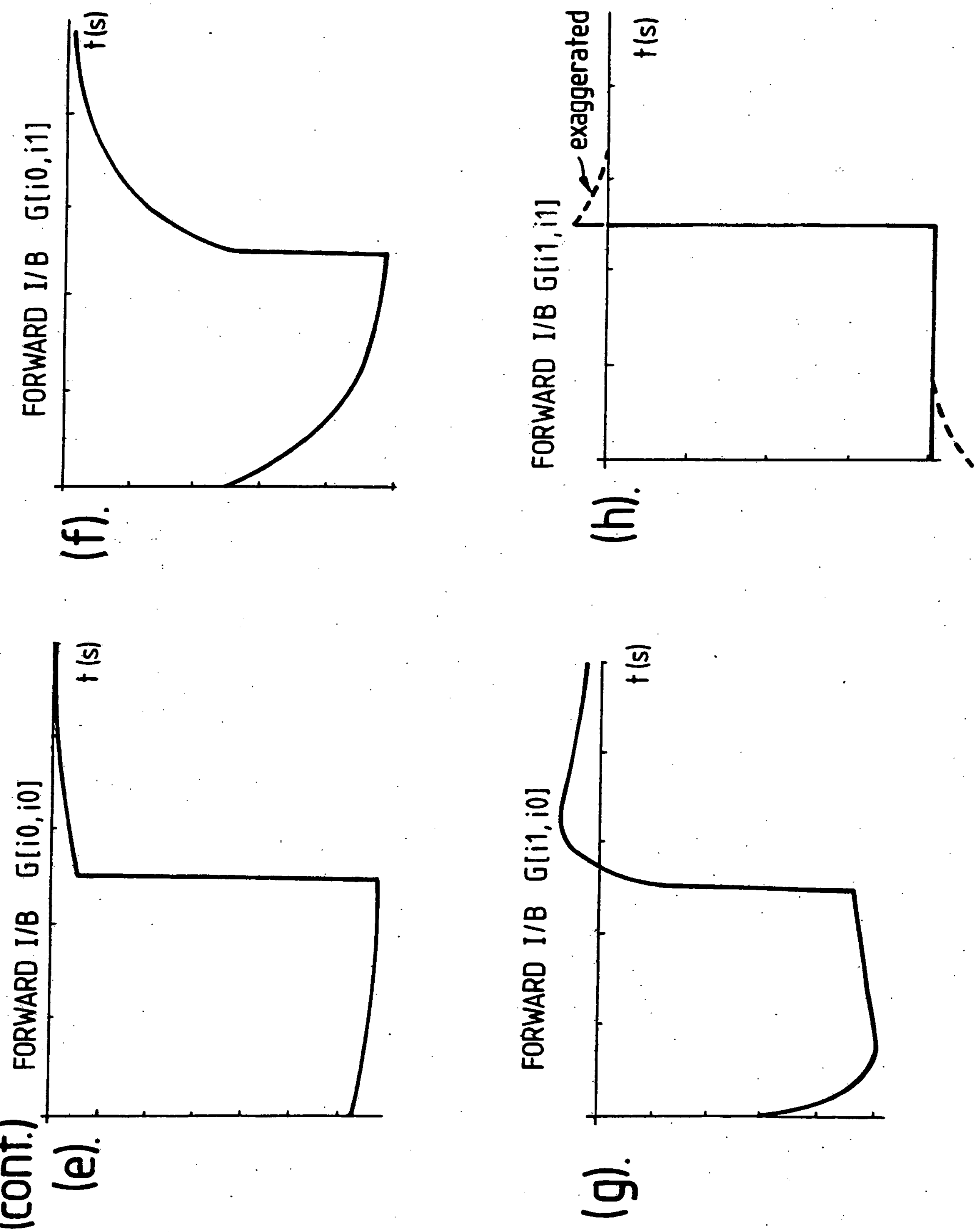

(e).
FORWARD I/B G[i0,i0]
t (s)
(f).
FORWARD I/B G[i0,i1]
t(s)
(g).
FORWARD I/B G[i1,i0]
t(s)
(h).
FORWARD I/B G[i1,i1]
exaggerated
t(s)

Fig.3(cont.)

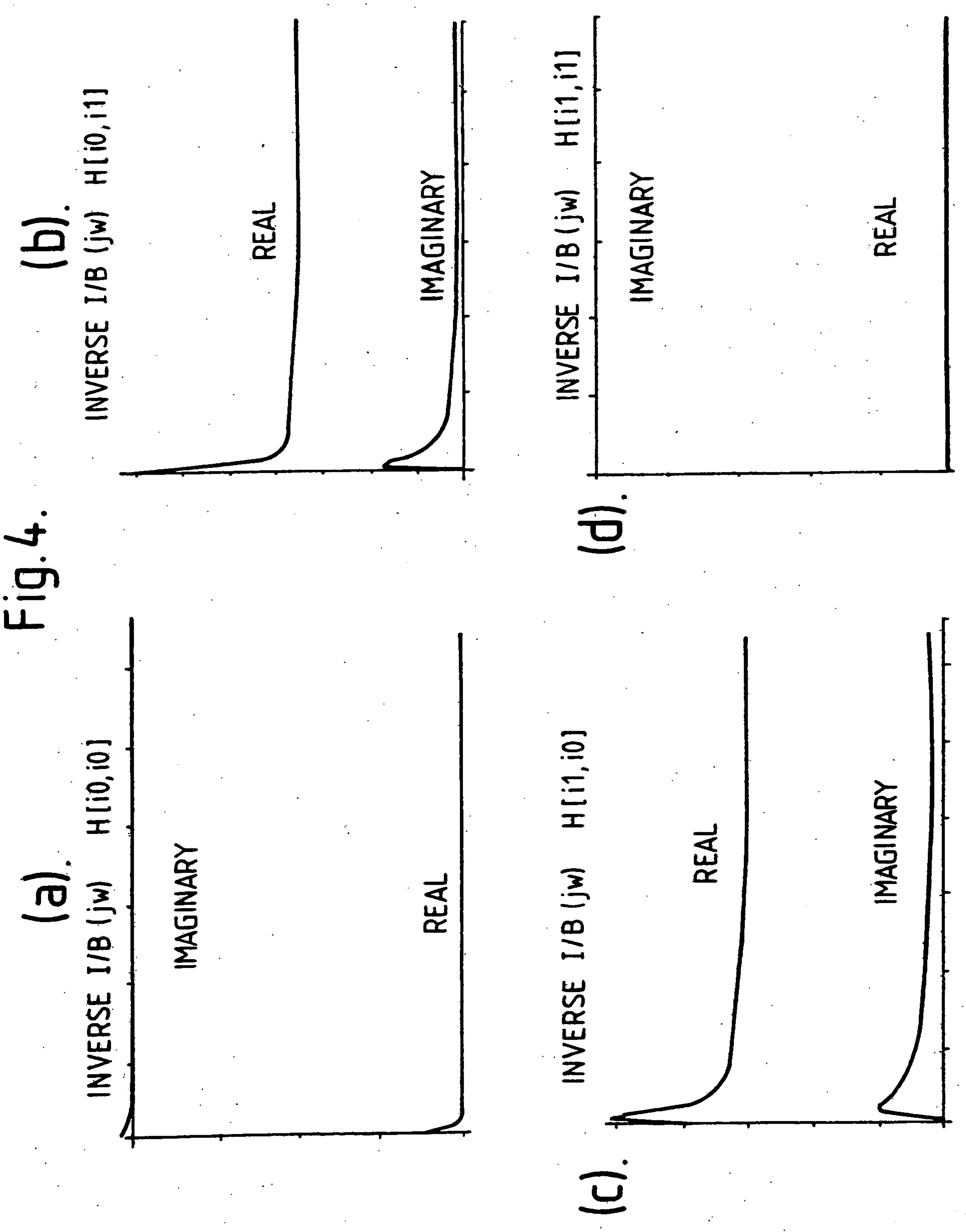

(a).
INVERSE I/B (jw) H[i0,i0]
IMAGINARY
REAL
(b).
INVERSE I/B (jw) H[i0,i1]
REAL
IMAGINARY
(c).
INVERSE I/B (jw) H[i1,i0]
REAL
IMAGINARY
(d).
INVERSE I/B (jw) H[i1,i1]
IMAGINARY
REAL

Fig.4.

Fig.4.(cont.)

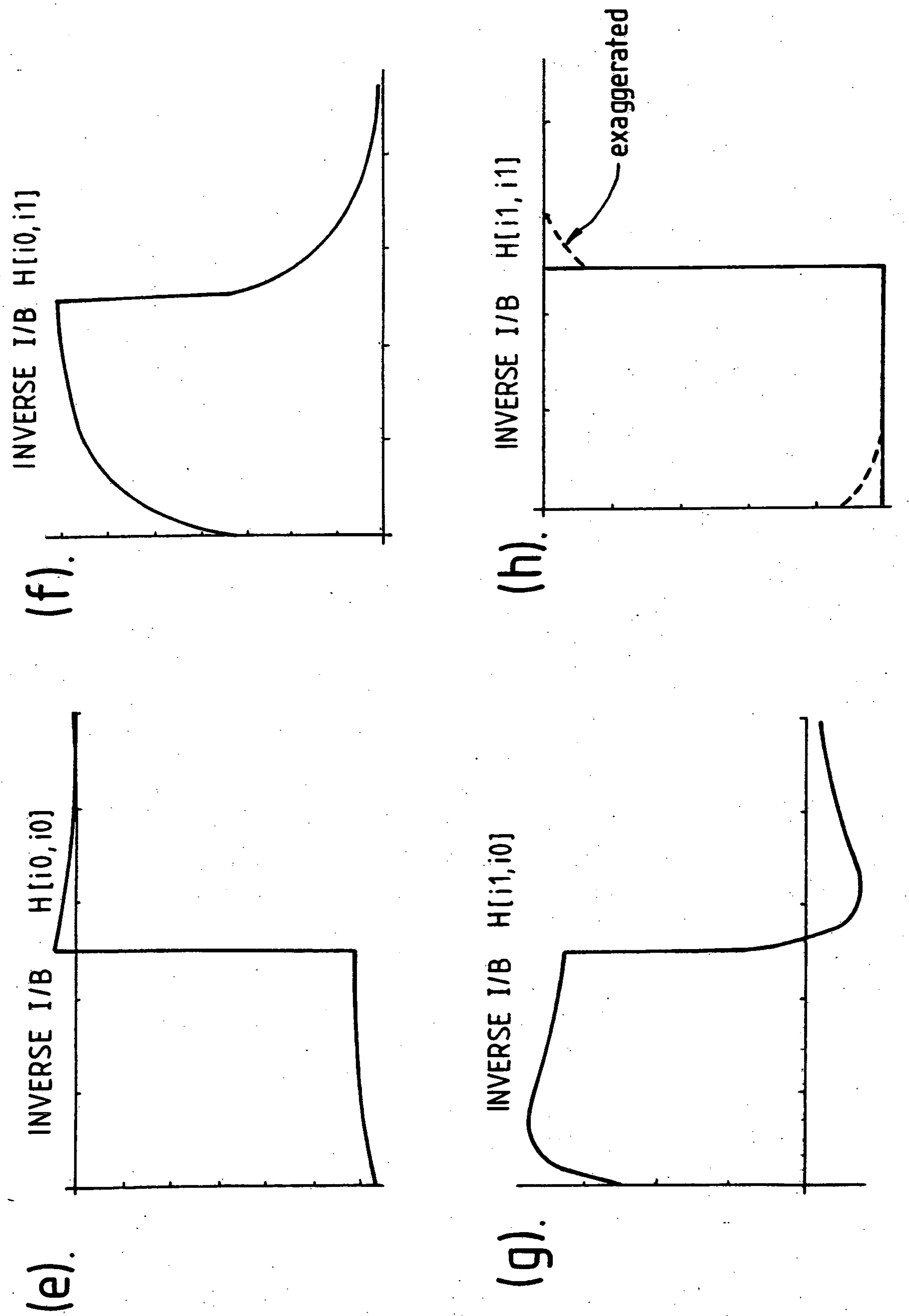

(f).
INVERSE I/B H[i0,i1]
(h).
INVERSE I/B H[i1,i1]
exaggerated
(e).
INVERSE I/B H[i0,i0]
(g).
INVERSE I/B H[i1,i0]

Fig.5.

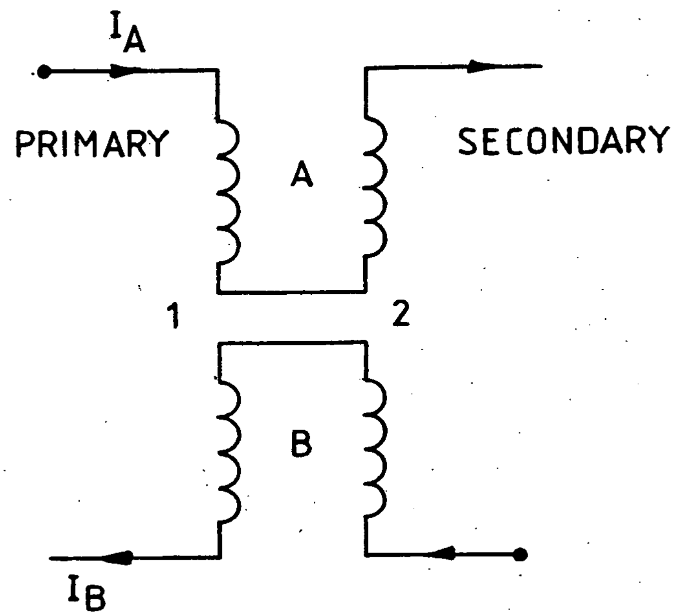
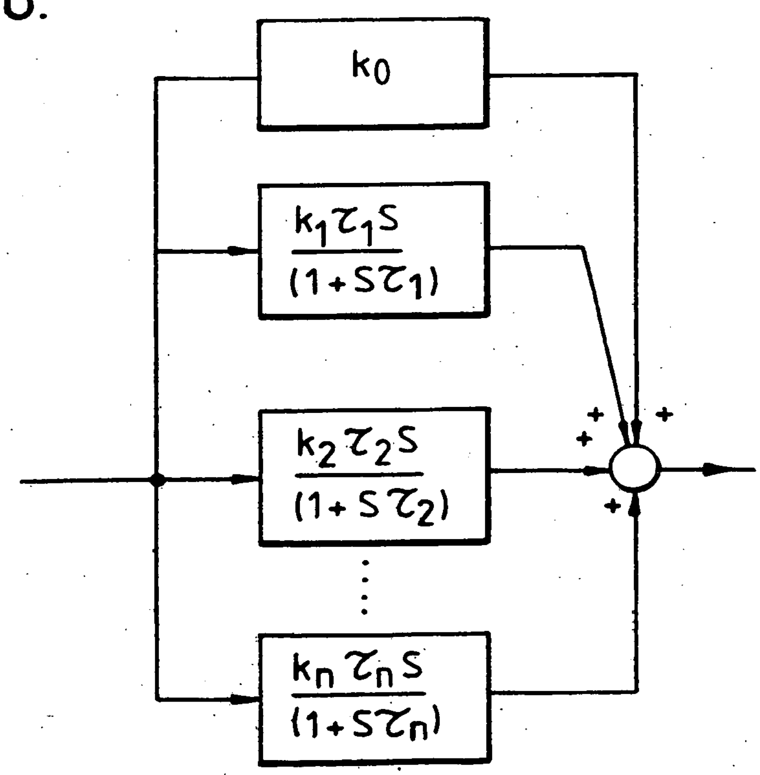

I_A
PRIMARY
SECONDARY
A
1
2
B
I_B

Fig.6.


k_0
$\frac{k_1 \tau_1 S}{(1+S\tau_1)}$
$\frac{k_2 \tau_2 S}{(1+S\tau_2)}$
$\frac{k_n \tau_n S}{(1+S\tau_n)}$
+
+
+
+

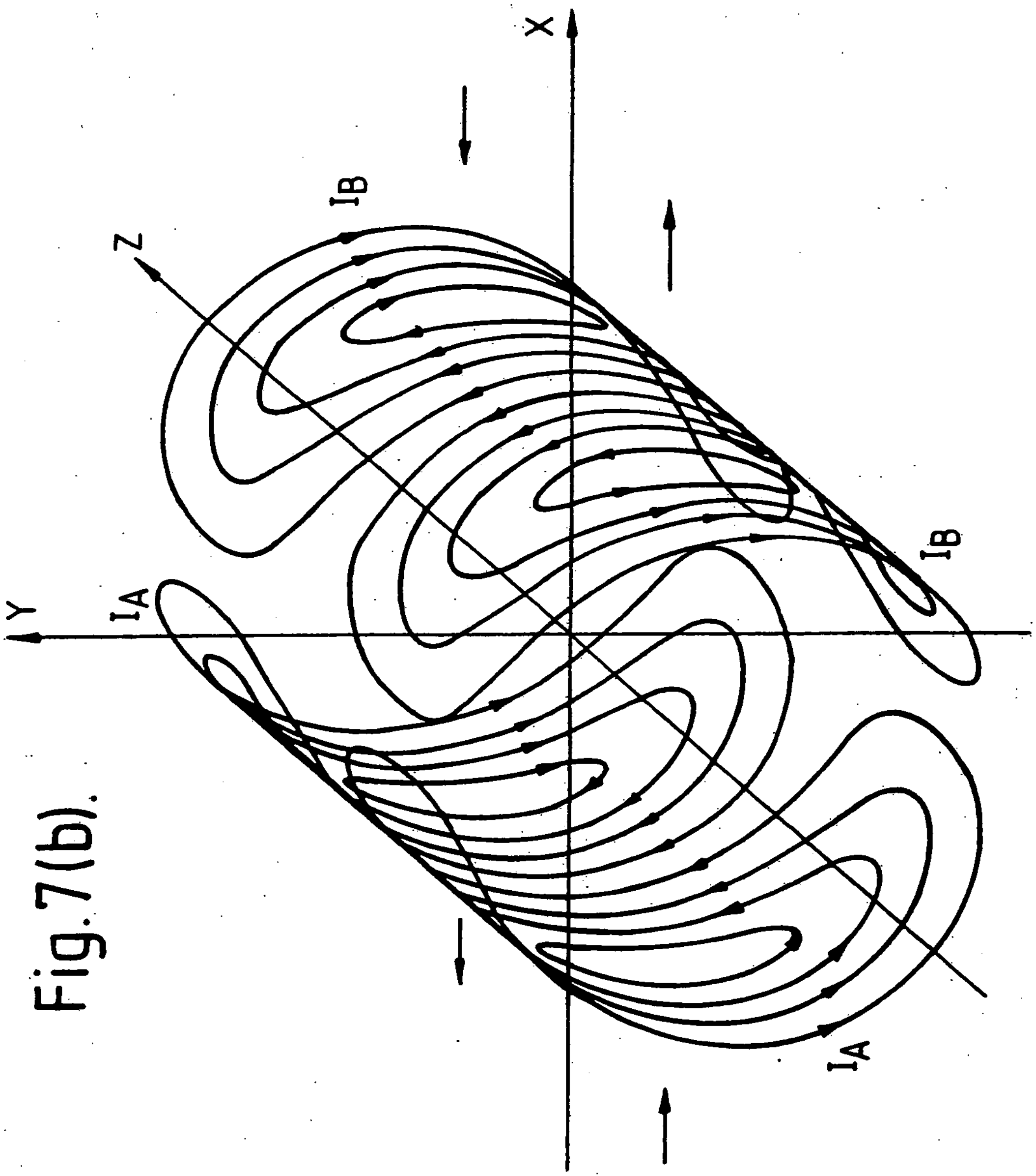


Fig. 7(b).

Fig.8.

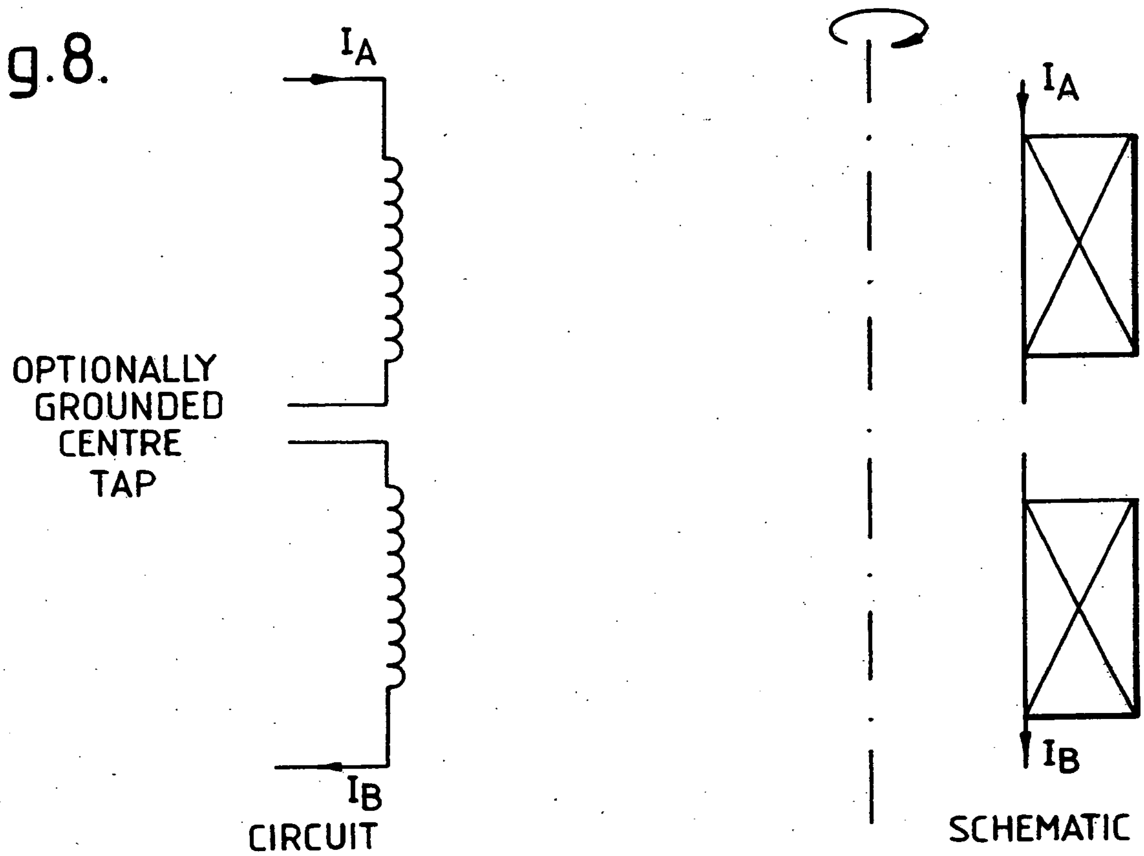
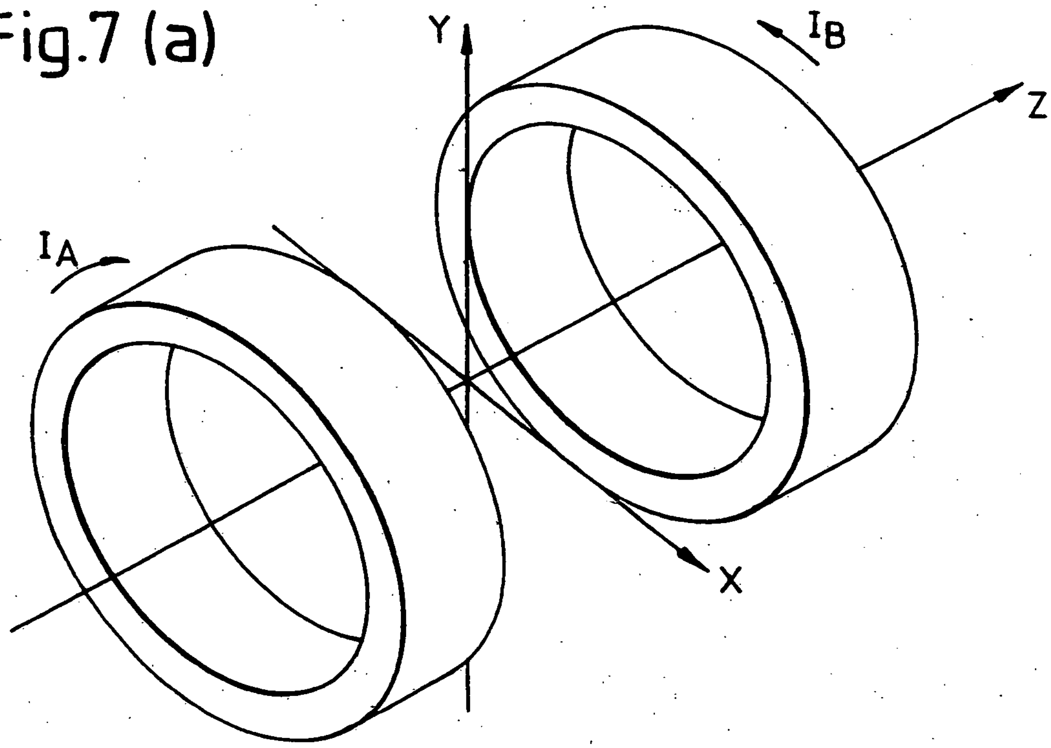

I_A
OPTIONALLY GROUNDED CENTRE TAP
I_B
CIRCUIT
I_A
I_B
SCHEMATIC

Fig.7 (a)


Y
I_B
Z
I_A
X

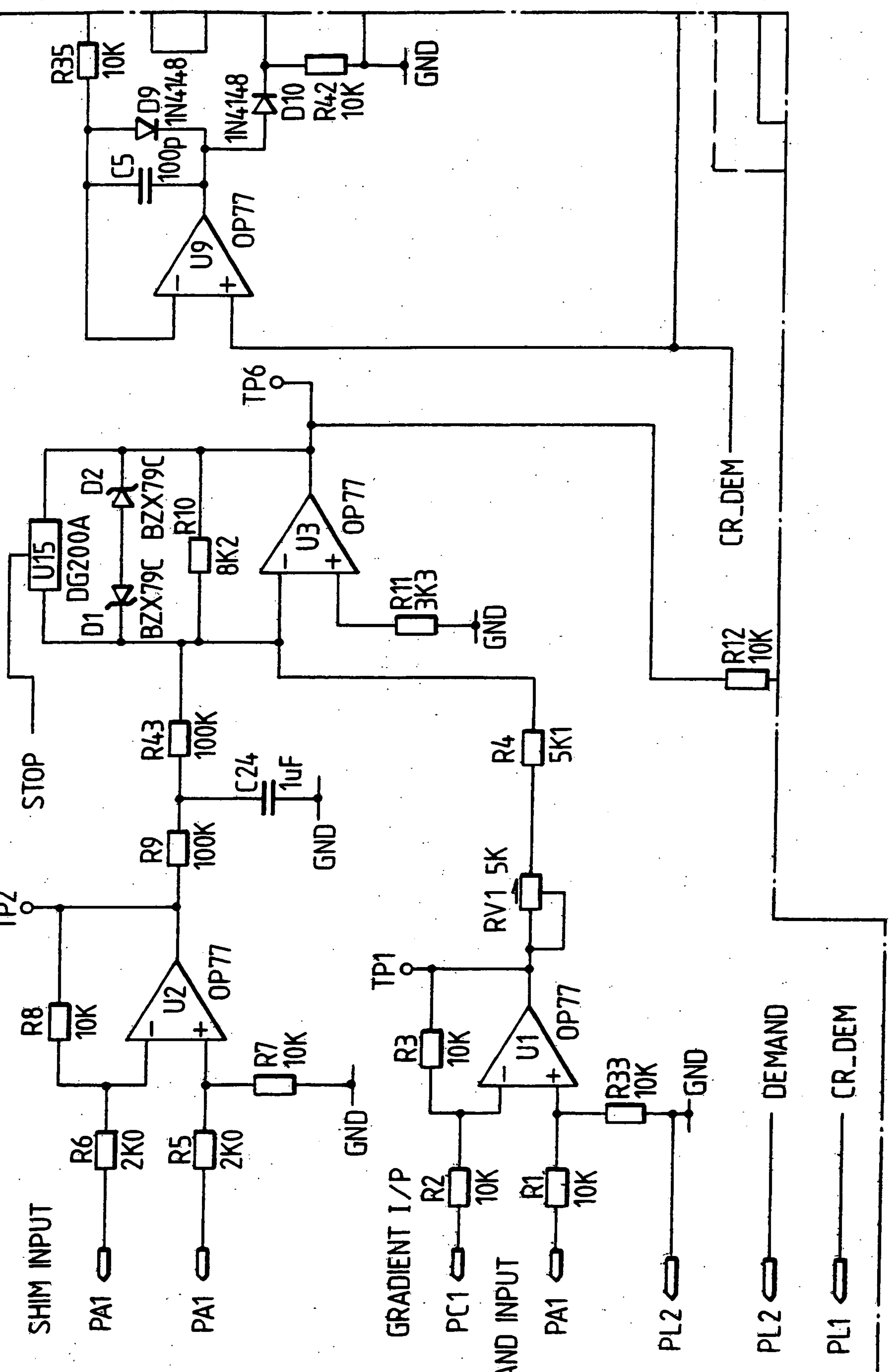

R35
10K
D9
1N4148
C5
100p
1N4148
D10
R42
10K
GND
U9
OP77
TP6
CR_DEM
D2
BZX79C
R10
8K2
U15
DG200A
D1
BZX79C
U3
OP77
R11
3K3
GND
R12
10K
STOP
R43
100K
C24
1uF
GND
R4
5K1
R9
100K
TP2
RV1 5K
TP1
R8
10K
U2
OP77
R7
10K
R3
10K
U1
OP77
R33
10K
GND
DEMAND
CR_DEM
R6
2K0
R5
2K0
GND
GRADIENT I/P
R2
10K
R1
10K
SHIM INPUT
PA1
PA1
PC1
DEMAND INPUT
PA1
PL2
PL2
PL1

Fig. 9a(i).

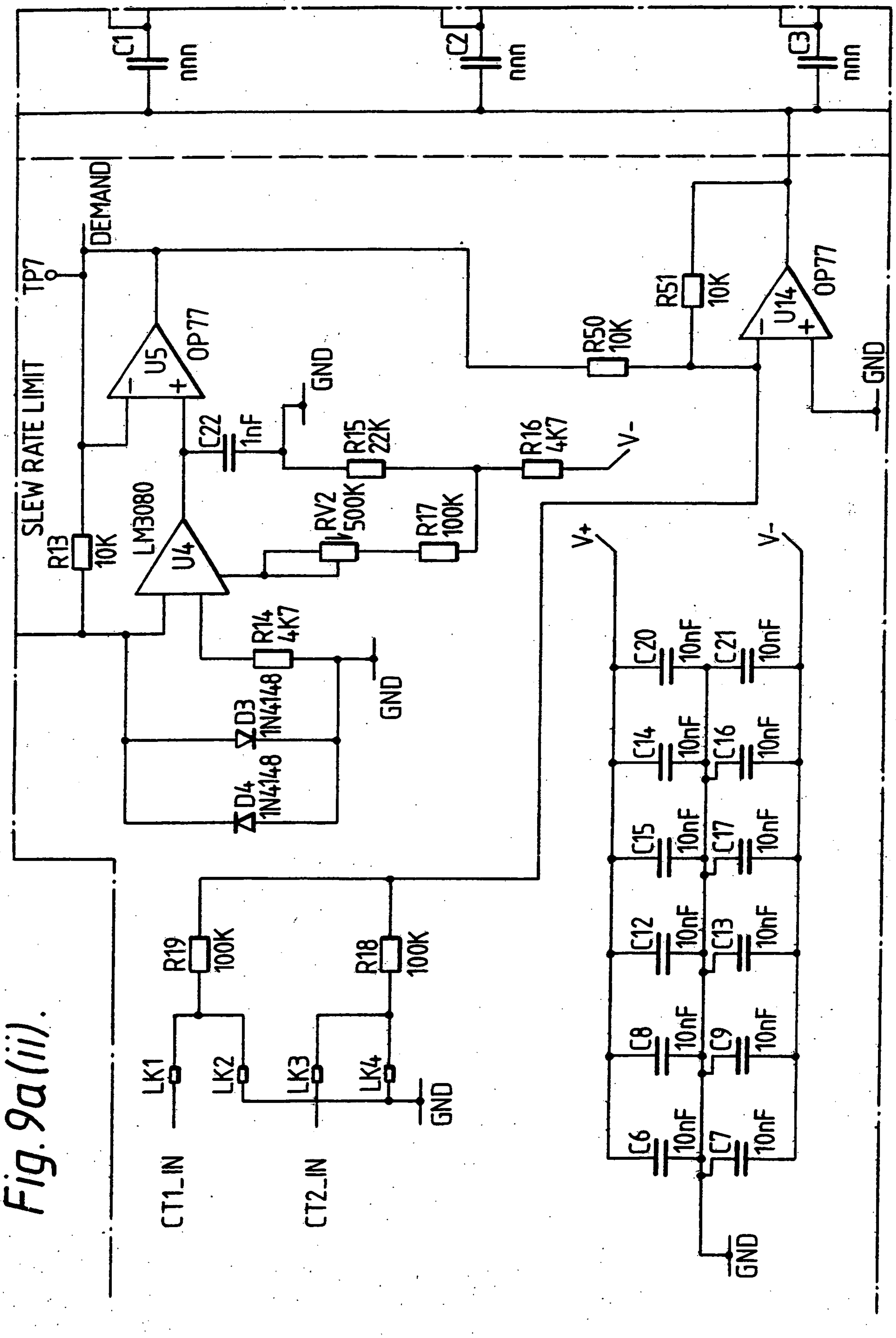

C1
nnn
C2
nnn
C3
nnn
DEMAND
TP7
SLEW RATE LIMIT
U5
OP77
GND
C22
1nF
R15
22K
R16
4K7
V-
R50
10K
R51
10K
U14
OP77
GND
R13
10K
LM3080
U4
RV2
500K
R17
100K
R14
4K7
GND
D3
1N4148
D4
1N4148
V+
V-
C20
10nF
C21
10nF
C14
10nF
C16
10nF
C15
10nF
C17
10nF
C12
10nF
C13
10nF
C8
10nF
C9
10nF
C6
10nF
C7
10nF
GND
R19
100K
R18
100K
LK1
LK2
LK3
LK4
GND
CT1_IN
CT2_IN

Fig. 9a (ii).

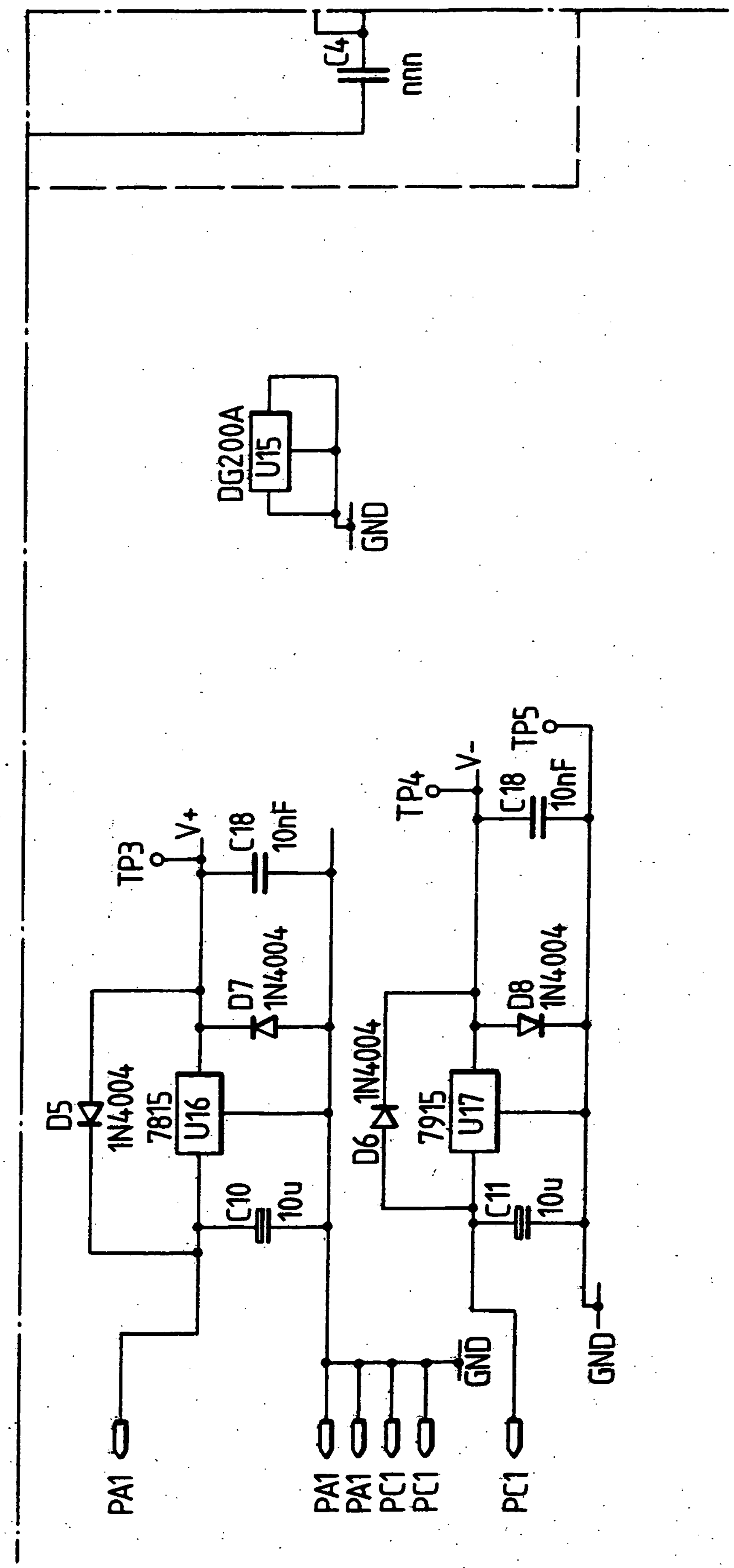

C4
nnn
DG200A
U15
GND
TP3
V+
C18
10nF
D7
1N4004
D5
1N4004
7815
U16
C10
10u
TP4
V-
TP5
C18
10nF
D8
1N4004
D6
1N4004
7915
U17
C11
10u
GND
GND
PA1
PA1
PA1
PC1
PC1
PC1

Fig.9a(iii).

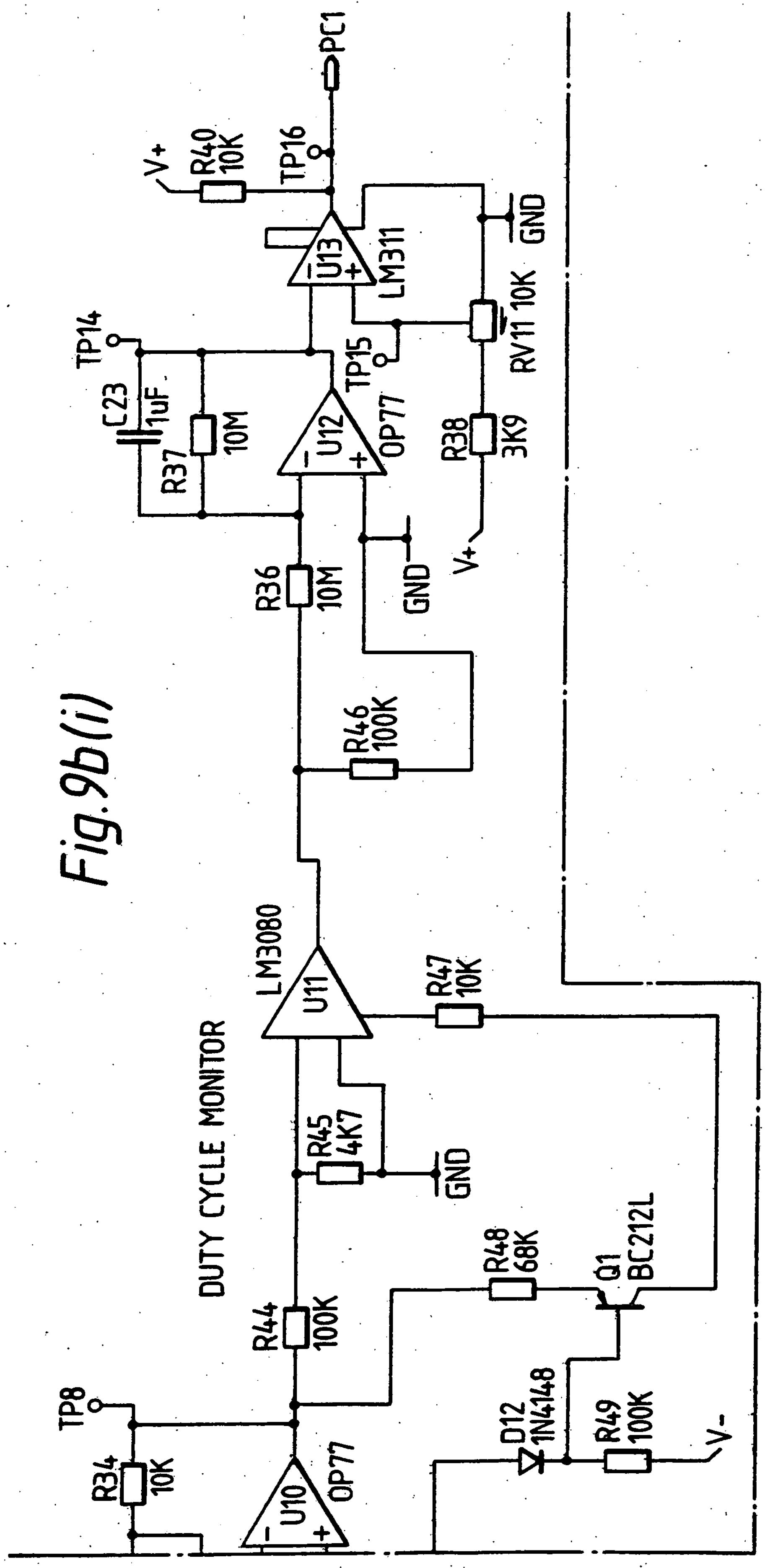

PC1
TP16
V+
R40 10K
U13
LM311
GND
RV11 10K
TP14
TP15
C23 1uF
R37 10M
U12
OP77
R38 3K9
V+
R36 10M
GND
R46 100K
LM3080
U11
R47 10K
DUTY CYCLE MONITOR
R45 4K7
GND
R48 68K
Q1 BC212L
R44 100K
TP8
D12 1N4148
R49 100K
V-
R34 10K
U10
OP77

Fig.9b(i)

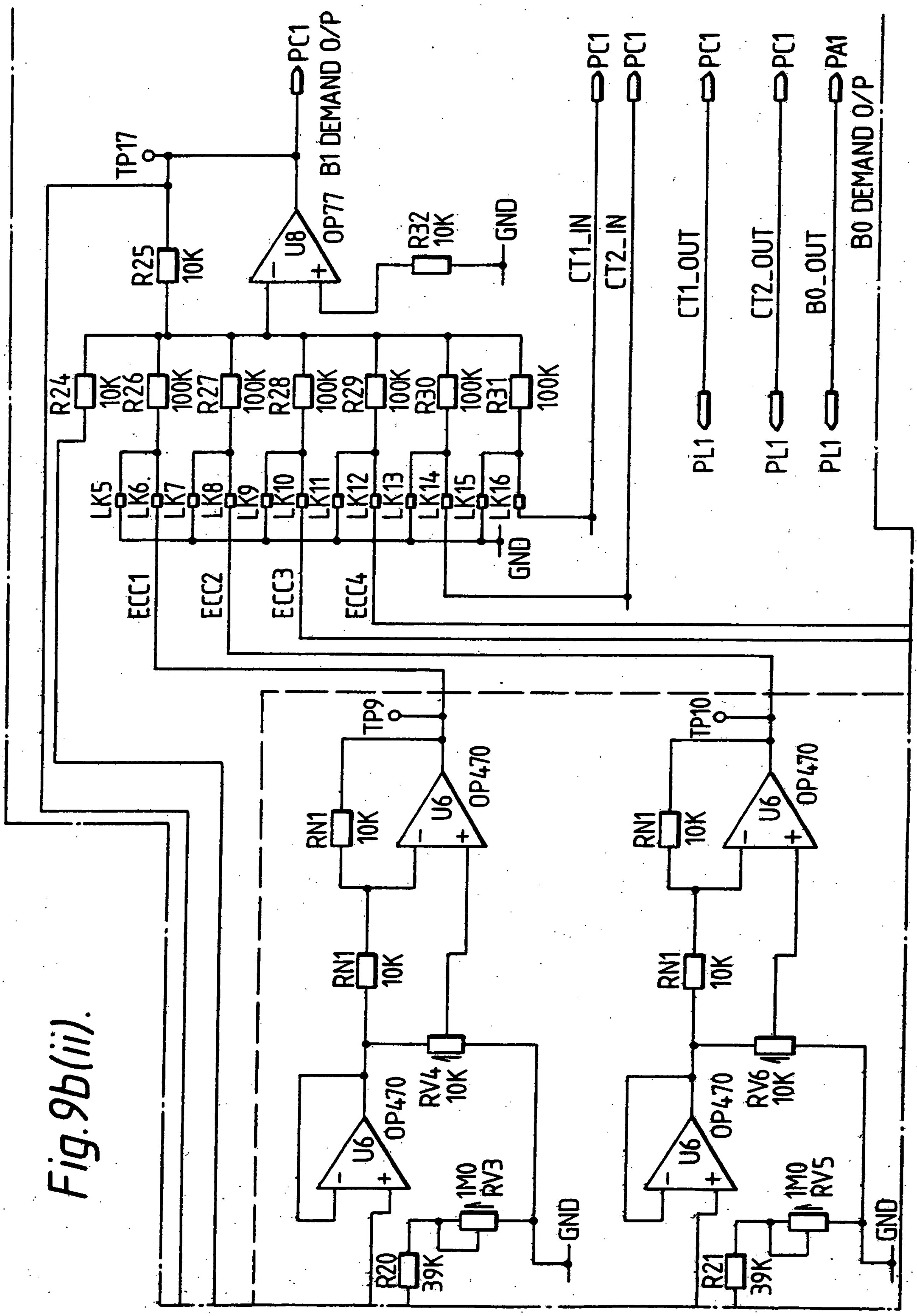
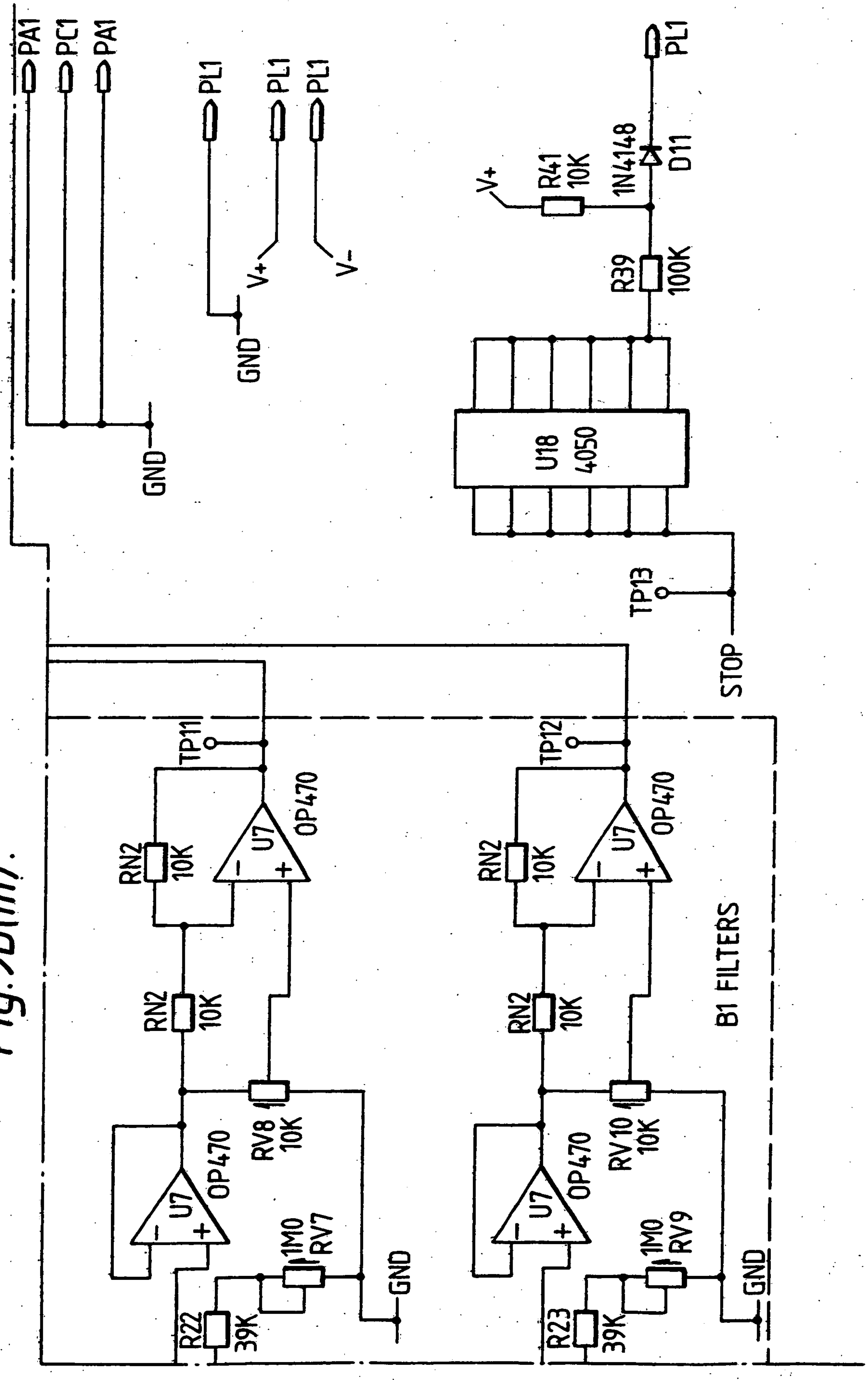

TP17
PC1
B1 DEMAND O/P
U8
OP77
R25
10K
R32
10K
GND
CT1_IN
CT2_IN
PC1
PC1
CT1_OUT
CT2_OUT
B0_OUT
PC1
PC1
PA1
B0 DEMAND O/P
PL1
PL1
PL1
R24
10K
R26
100K
R27
100K
R28
100K
R29
100K
R30
100K
R31
100K
LK5
LK6
LK7
LK8
LK9
LK10
LK11
LK12
LK13
LK14
LK15
LK16
GND
ECC1
ECC2
ECC3
ECC4
TP9
TP10
U6
OP470
RN1
10K
RV4
10K
RV6
10K
1M0
RV3
RV5
R20
39K
R21
39K
GND

Fig.9b(ii).

Fig. 9b(iii).


PA1
PC1
PA1
GND
PL1
PL1
PL1
GND
V+
V-
PL1
D11
1N4148
R41
10K
V+
R39
100K
U18
4050
TP13
STOP
TP11
TP12
RN2
10K
RN2
10K
U7
OP470
RV8
10K
1M0
RV7
R22
39K
GND
RN2
10K
RN2
10K
U7
OP470
RV10
10K
1M0
RV9
R23
39K
GND
B1 FILTERS

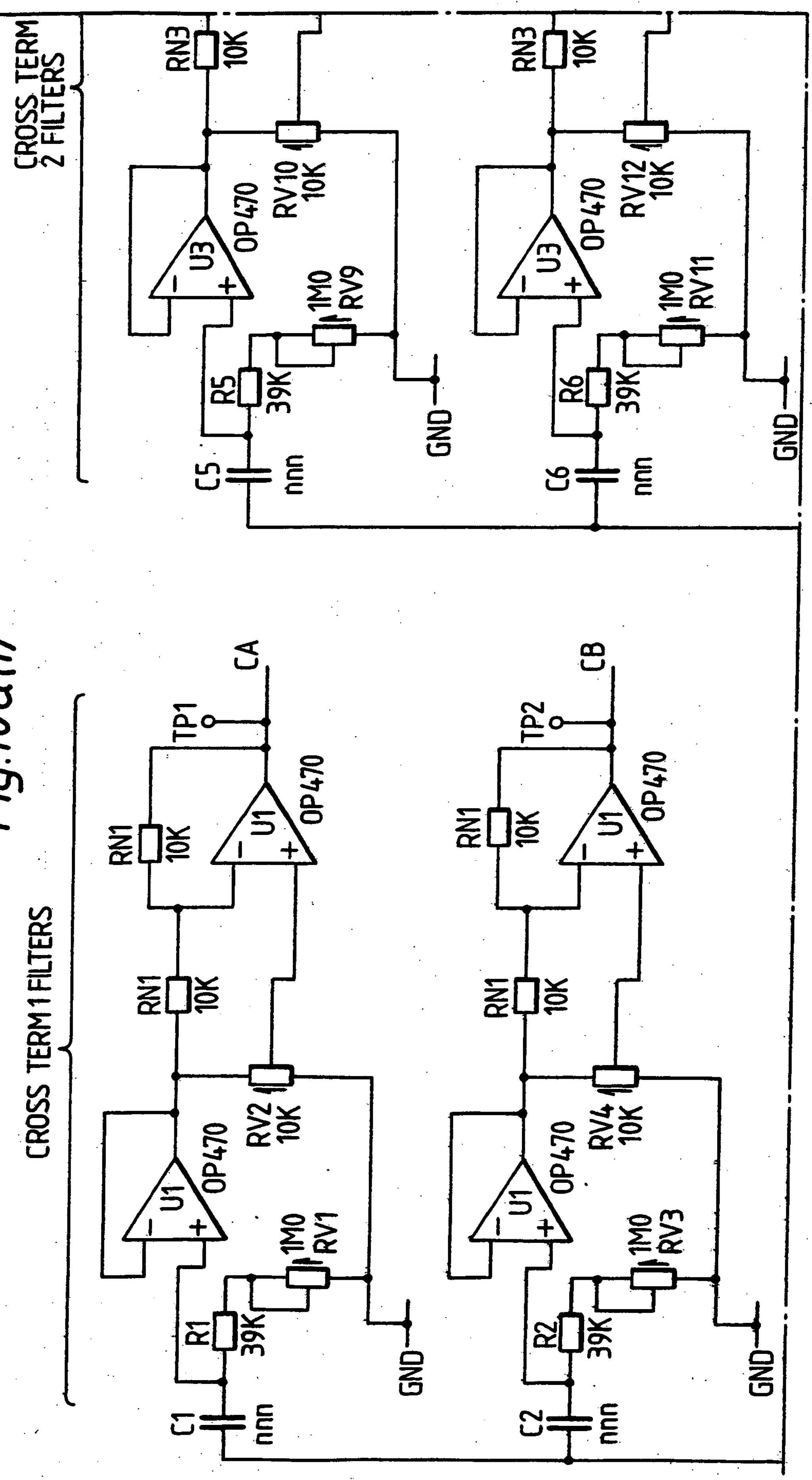

CROSS TERM 2 FILTERS
RN3 10K
RV10 10K
OP470
U3
1M0 RV9
R5 39K
C5 nnn
GND
RN3 10K
RV12 10K
OP470
U3
1M0 RV11
R6 39K
C6 nnn
GND
CROSS TERM 1 FILTERS
CA
TP1
RN1 10K
U1
OP470
RN1 10K
RV2 10K
OP470
U1
1M0 RV1
R1 39K
C1 nnn
GND
CB
TP2
RN1 10K
U1
OP470
RN1 10K
RV4 10K
OP470
U1
1M0 RV3
R2 39K
C2 nnn
GND

Fig.10a(i)

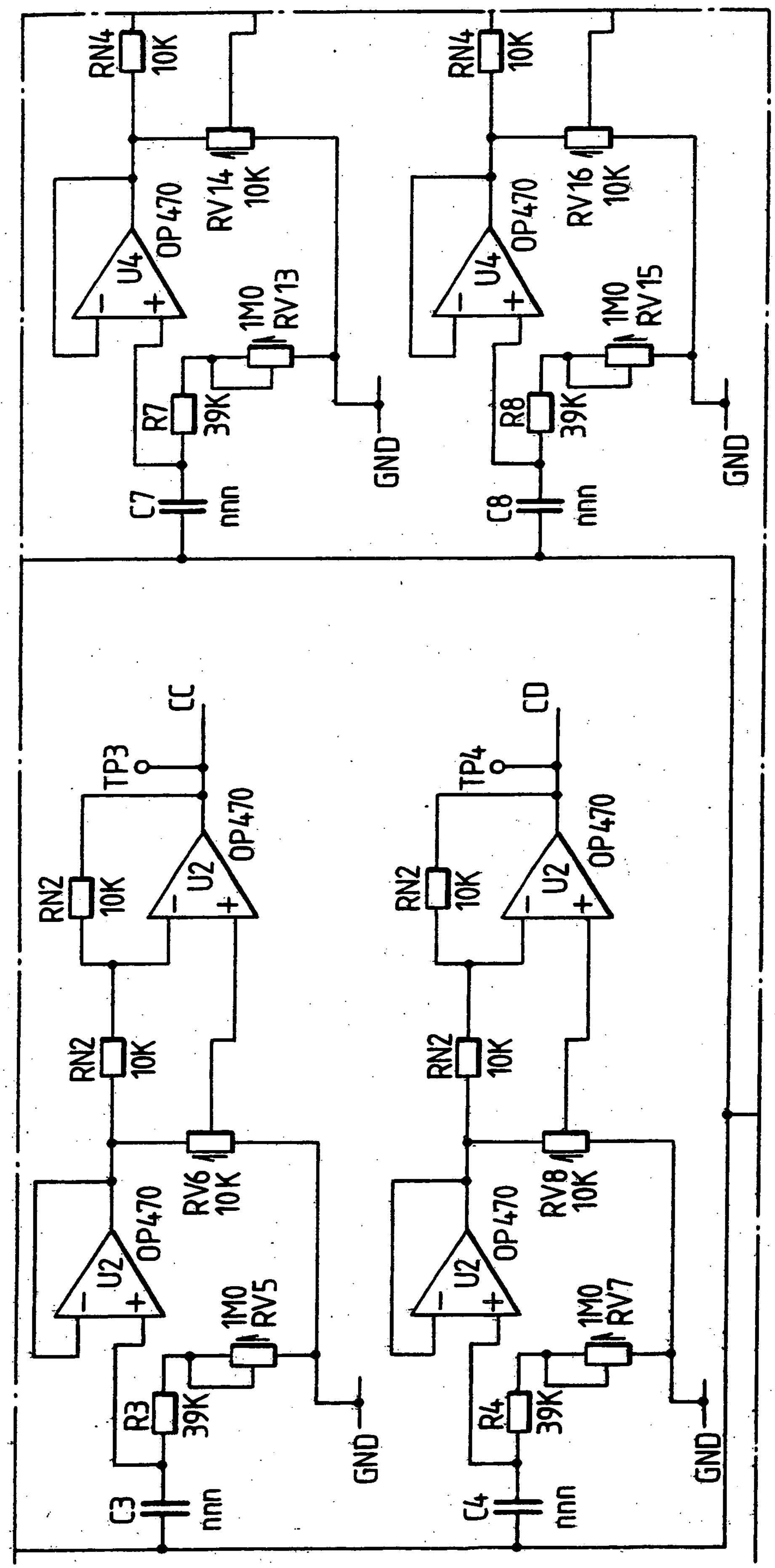

RN4
10K
RV14
10K
OP470
U4
1M0
RV13
R7
39K
C7
nnn
GND
RN4
10K
RV16
10K
OP470
U4
1M0
RV15
R8
39K
C8
nnn
GND
CC
TP3
OP470
U2
RN2
10K
RN2
10K
RV6
10K
OP470
U2
1M0
RV5
R3
39K
C3
nnn
GND
CD
TP4
OP470
U2
RN2
10K
RN2
10K
RV8
10K
OP470
U2
1M0
RV7
R4
39K
C4
nnn
GND

Fig.10a(ii)

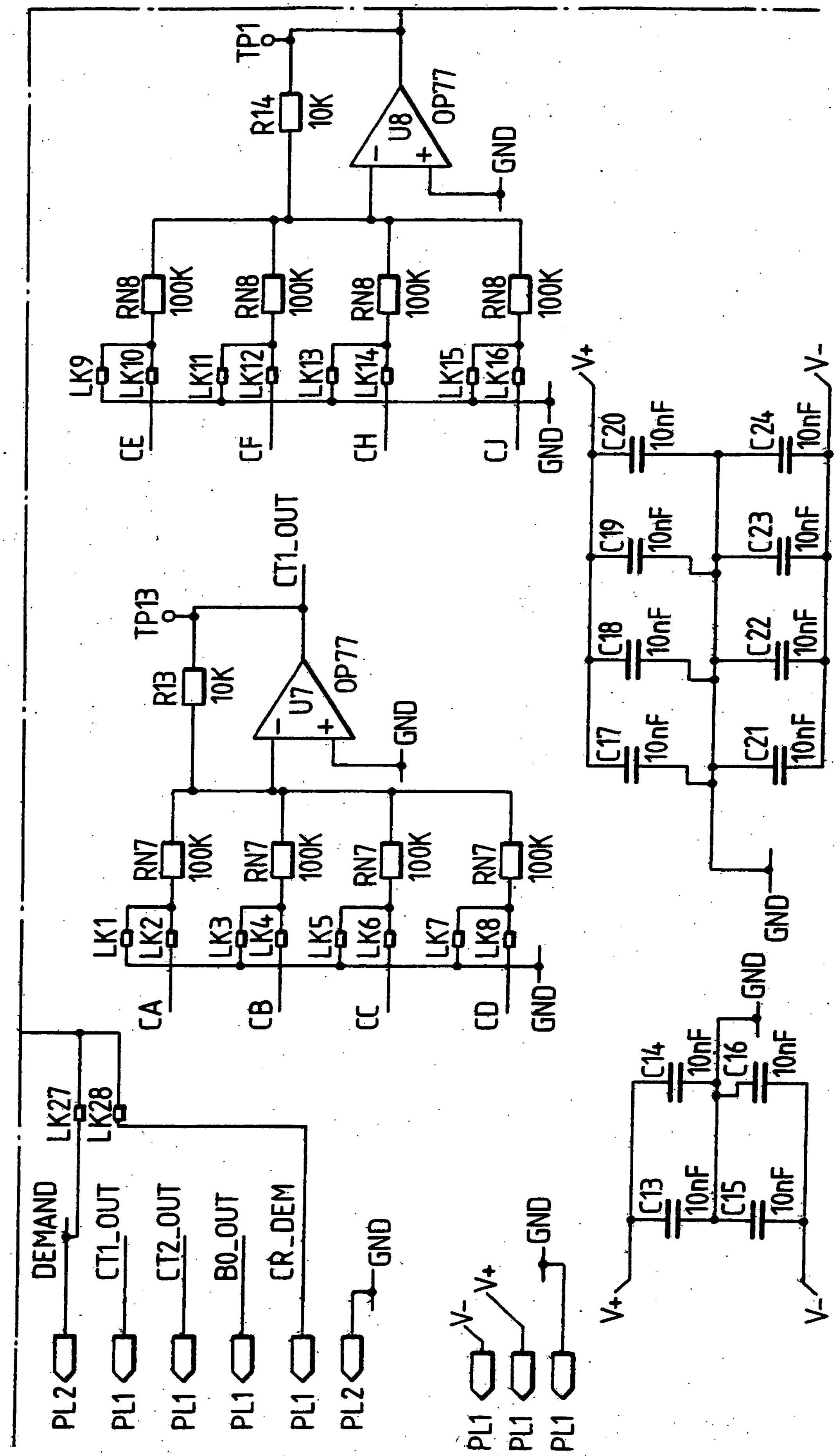

TP1
R14
10K
U8
OP77
GND
RN8
100K
LK9
LK10
LK11
LK12
LK13
LK14
LK15
LK16
CE
CF
CH
CJ
CT1_OUT
TP13
R13
U7
RN7
LK1
LK2
LK3
LK4
LK5
LK6
LK7
LK8
CA
CB
CC
CD
V+
V-
C13
C14
C15
C16
C17
C18
C19
C20
C21
C22
C23
C24
10nF
LK27
LK28
DEMAND
CT2_OUT
B0_OUT
CR_DEM
PL1
PL2

Fig.10a(iii).

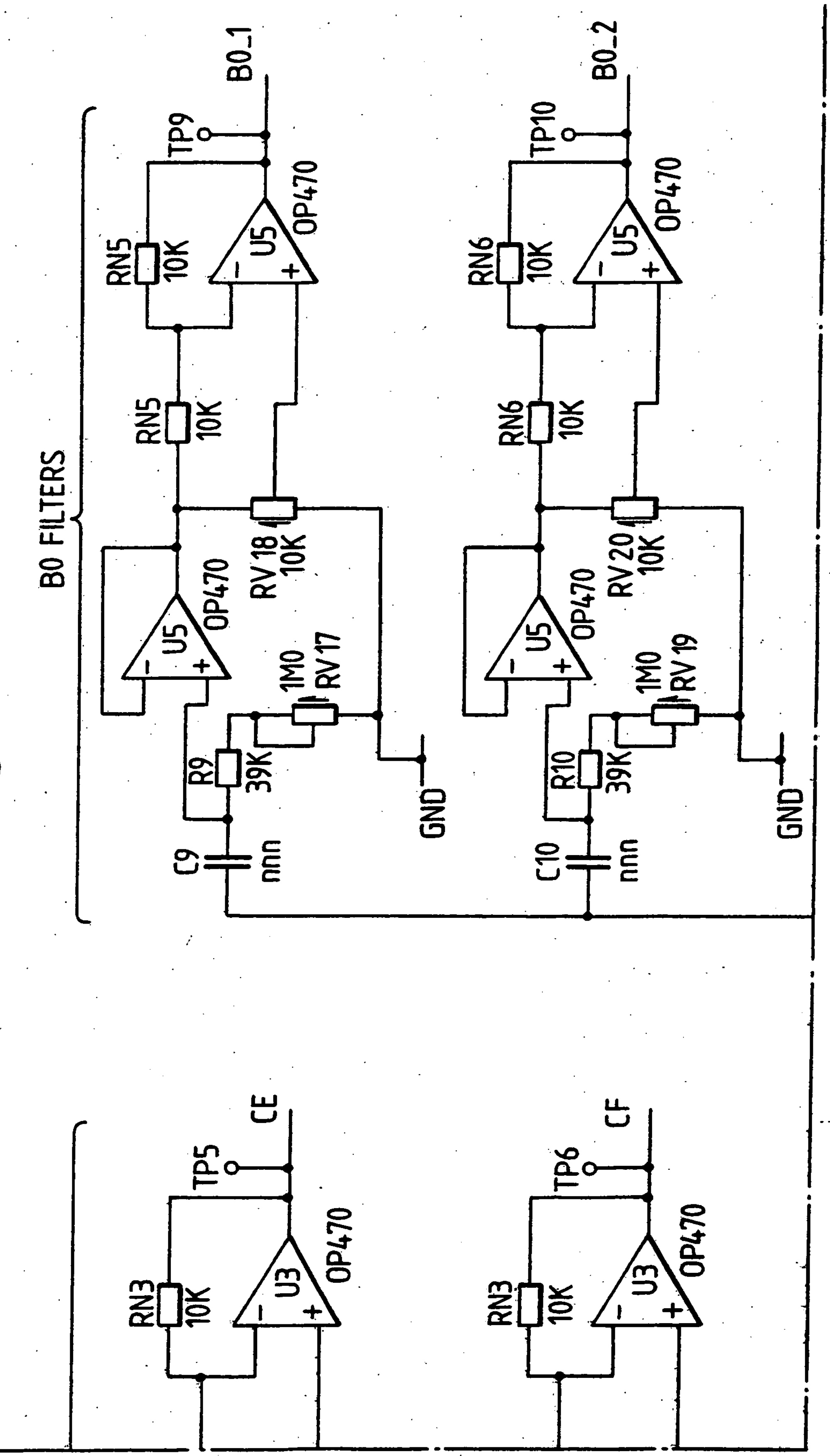
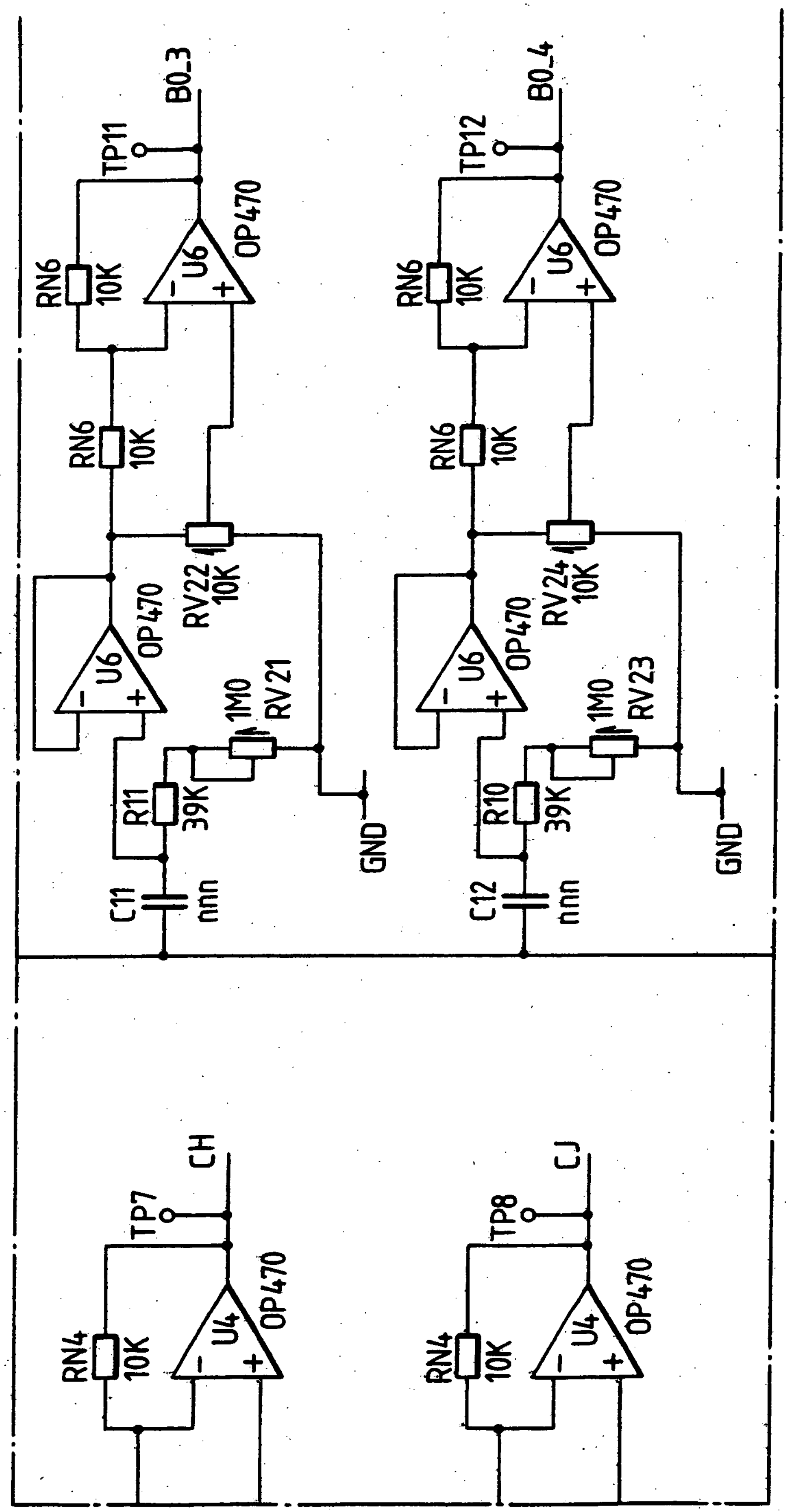

B0_1
TP9
RN5
10K
U5
OP470
RN5
10K
RV18
10K
U5
OP470
1M0
RV17
R9
39K
GND
C9
nnn
B0 FILTERS
B0_2
TP10
RN6
10K
U5
OP470
RN6
10K
RV20
10K
U5
OP470
1M0
RV19
R10
39K
GND
C10
nnn
CE
TP5
RN3
10K
U3
OP470
CF
TP6
RN3
10K
U3
OP470

Fig.10b(i).


B0_3
TP11
RN6
10K
U6
OP470
RN6
10K
RV22
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U6
OP470
1M0
RV21
R11
39K
C11
nnn
GND
B0_4
TP12
RN6
10K
U6
OP470
RN6
10K
RV24
10K
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OP470
1M0
RV23
R10
39K
C12
nnn
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CH
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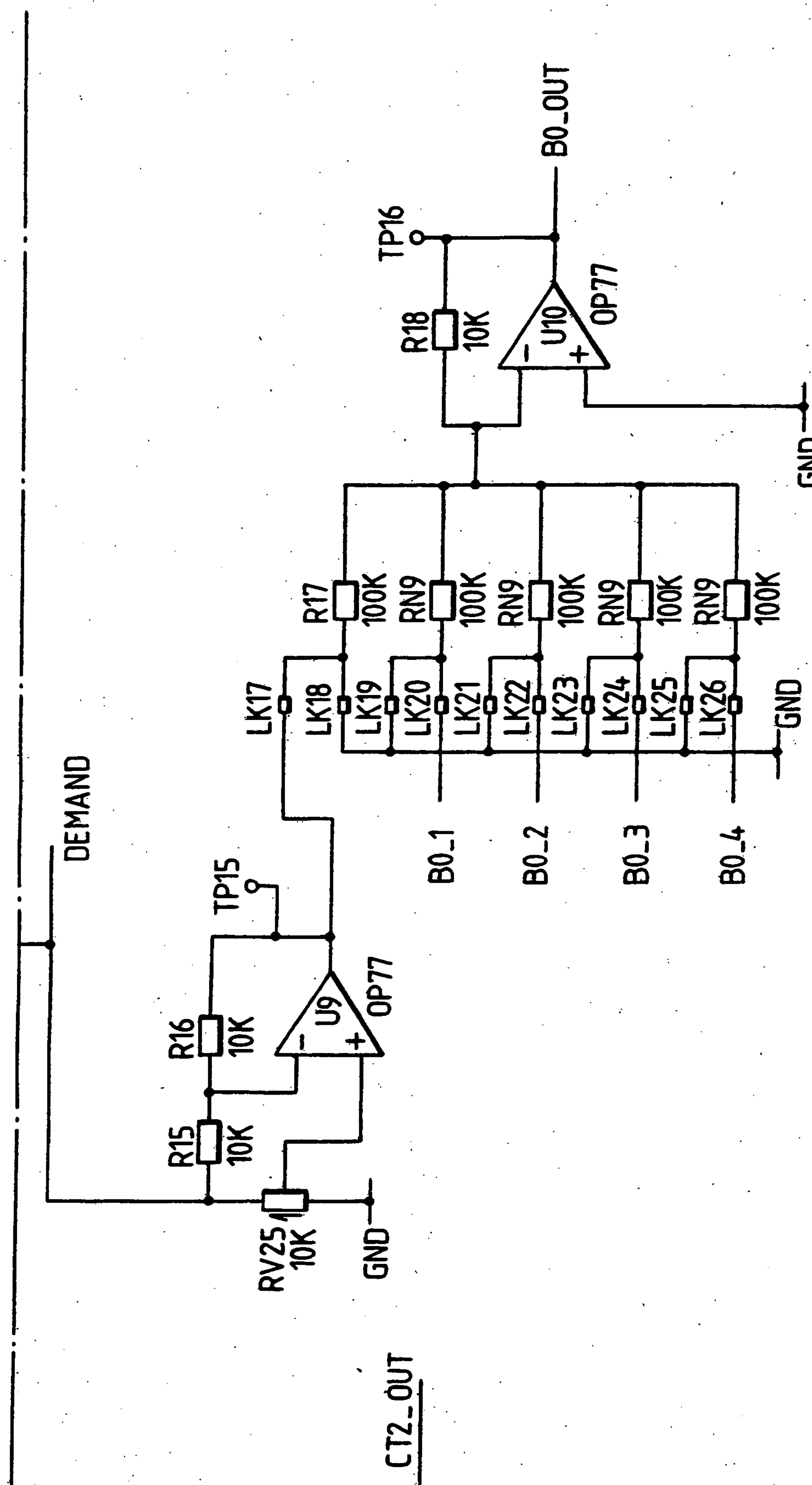
RN4
10K
U4
OP470
CJ
TP8
RN4
10K
U4
OP470

Fig.10b(ii).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TP16
R15 10K
R16 10K
R17 100K
R18 10K
RV25 10K
U9 OP77
U10 OP77
RN9 100K
RN9 100K
RN9 100K
RN9 100K
LK17
LK18
LK19
LK20
LK21
LK22
LK23
LK24
LK25
LK26
GND
GND
GND
B0_1
B0_2
B0_3
B0_4
B0_OUT

Fig.10b(iii).

INTERNATIONAL SEARCH REPORT

International Application No PCT/GB 93/00082

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all)[6]

According to International Patent Classification (IPC) or to both National Classification and IPC

Int.Cl. 5 G01R33/38

II. FIELDS SEARCHED

Minimum Documentation Searched[7]

Classification System	Classification Symbols
Int.Cl. 5	G01R

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched[8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT[9]

Category °	Citation of Document, [11] with indication, where appropriate, of the relevant passages [12]	Relevant to Claim No.[13]
Y	US,A,4 928 063 (D.A. LAMPMAN ET AL.) 22 May 1990 see column 2, line 3 - column 3, line 10 see column 4, line 6 - column 6, line 66; figures 1A,1B	1,3,6,7
A		9,10,12, 13

Y	EP,A,0 361 574 (N.V. PHILIPS' GLOEILAMPENFABRIEKEN) 4 April 1990 see column 2, line 47 - column 3, line 19 see column 6, line 2 - column 7, line 21; figures 2A-2C	1,3,6,7
A		12

	-/--	

° Special categories of cited documents : [10]

"A" document defining the general state of the art which is not considered to be of particular relevance

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"&" document member of the same patent family

IV. CERTIFICATION

3

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
15 APRIL 1993	21 APR 1993
International Searching Authority	**Signature of Authorized Officer**
EUROPEAN PATENT OFFICE	HORAK G.I.

III. DOCUMENTS CONSIDERED TO BE RELEVANT (CONTINUED FROM THE SECOND SHEET)

Category °	Citation of Document, with indication, where appropriate, of the relevant passages	Relevant to Claim No.
A	DE,A,4 020 213 (SIEMENS AG) 9 January 1992 see column 1, line 47 - column 3, line 22 see column 6, line 42 - column 8, line 2; figure 2 ---	1,3,6,7
A	JOURNAL OF MAGNETIC RESONANCE. vol. 90, no. 2, 1 November 1990, ORLANDO, MN US pages 264 - 278 P. JEHENSON ET AL. 'ANALYTICAL METHOD FOR THE COMPENSATION OF EDDY-CURRENT EFFECTS INDUCED BY PULSED MAGNETIC FIELD GRADIENTS IN NMR SYSTEMS' cited in the application see the whole document ---	1,6
A	US,A,4 437 053 (R.F. BAX) 13 March 1984 see column 1, line 28 - column 2, line 21 see column 3, line 15 - column 4, line 68; figure 1 ---	1,6,12
A	EP,A,0 291 157 (PICKER INTERNATIONAL, INC.) 17 November 1988 see page 2, line 36 - page 4, line 12 see page 4, line 49 - page 6, line 38; figures 1,3 ---	1,3,6,12
A	US,A,4 585 995 (D.C. FLUGAN) 29 April 1986 cited in the application see column 1, line 39 - column 2, line 30 ---	1,6,12
P,X	EP,A,0 476 321 (SIEMENS AKTIENGESELLSCHAFT) 25 March 1992 see column 3, line 42 - column 7, line 30; figures 2,4,5,6,13 -----	1,6

ANNEX TO THE INTERNATIONAL SEARCH REPORT ON INTERNATIONAL PATENT APPLICATION NO.

GB 9300082
SA 68787

This annex lists the patent family members relating to the patent documents cited in the above-mentioned international search report.
The members are as contained in the European Patent Office EDP file on 15/04/
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		JP-A-	2107230	19-04-90
		US-A-	5025217	18-06-91
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For more details about this annex : see Official Journal of the European Patent Office, No. 12/82